NRL Memorandum Report 2707

Satellite Detection and Surveillance

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The present National Space Surveillance capability has been surveyed, and specific areas of interest have been identified in the high-altitude regime (above 7500 n. mi.) such as catalogue maintenance and orbit computation, active space defense, intruder detection, and parameter definition for use in advanced planning. A study into methods of improving the high-altitude capability of the U.S. Naval Space Surveillance System (WS has also been made, which indicates that a cost-effective program
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Abstract

The present National Space Surveillance capability has been surveyed, and specific areas of interest have been identified in the high-altitude regime (above 7500 n. mi.) such as catalogue maintenance and orbit computation, active space defense, intruder detection, and parameter definition for use in advanced planning. A study into methods of improving the high-altitude capability of the U.S. Naval Space Surveillance System (WS-434) has also been made, which indicates that a cost-effective program extending capability to synchronous altitude is feasible for 10 m^2 sized objects. The impact of this capability on space defense and on the Timation program is suggested. A suggested development plan of WS-434 upgrading is included in a Technical Addendum under separate cover.

SATELLITE DETECTION AND SURVEILLANCE

INTRODUCTION

NRL has conducted an in-house investigation into current DoD satellite detection and space surveillance capabilities and planned new areas of activity. The purpose of the study is to identify new areas of development or modifications of existing capability that will be necessary to meet present and future Navy and DoD space-surveillance requirements, and to outline a development effort to meet some of these requirements. A proposed development program for WS-434 improvement is outlined in the technical addendum at the end of this report.

BACKGROUND

Operational DoD space surveillance is under the control and supervision of the North American Air Defense Command (NORAD). The NORAD Space Defense Center (SDC) is specifically charged with this task. Its present and planned capability is documented in Ref. 1 and 2. The present capability for detection of satellites depends on the Naval Space Surveillance System (WS-434), the AN/FPS-85 radar developed by the Air Force, the Air Force Spacetrack System WS-496L, and the Ballistic Missile Early Warning System (BMEWS). All of these systems, collectively known as SPADATS, employ radar-type systems. Although Baker-Nunn cameras are used for very-long-range tracking, there are no optical surveillance sensors supplying data to SDC because of the limitations of such devices for detection. The present system is considered by NORAD to be adequate in some areas and seriously limited in others.

Over the years the coverage, capability, accuracy, reliability, and cost effectiveness of the entire SPADATS system and the individual sensors have been analyzed many times. Reference 3 is a study by Philco-Ford in 1961 of the SPADATS system coverage and capability, and Ref. 4 is a similar study made by RCA in 1963. It emphasizes the end products of ephemeris accuracy and time constants. Reference 5, a 1966 study by Fairchild-Hiller Republic Aviation Division for BUWEPS RTAD-23, emphasizes the use of SPADATS in active defense against postulated orbital threats. An analysis of the first-pass detection capability of the SPADATS system appears in an Air Force study of 1963 Ref (6). A statement of future policy on the detection and tracking

of satellites is contained in the so-called DATOS report, promulgated in 1965 by the Secretary of Defense (Ref. 7), which had a profound effect on future R&D. The DATOS report was the result of a study of the entire subject of space surveillance by an ad hoc working group under Daniel Fink; it effectively defined the space-defense posture of this country as it exists today. Mr. Fink has recently chaired a special defense panel under DDR&E's Defense Science Advisory Board examining the entire antisatellite problem anew Ref (8).

Four general areas of interest in space surveillance were identified during this study. All are dependent upon the SDC and high and low altitude capability. They are:

1. Data collection and orbit computation
2. Active space defense
3. Support for advanced military space systems planning
4. Protection of certain strategically important satellite systems.

DATA COLLECTION AND ORBIT COMPUTATION

"Traditional" space surveillance, data collection and orbit computation, was developed first and is required in varying degrees to solve problems in the other areas. This concept of surveillance maintains the catalog of satellite population as a set of orbital elements. These orbital elements are also used for scientific purposes, such as investigation of the upper atmosphere, the gravity field of the earth, and perturbations due to the other bodies of the solar system. The orbital elements, including launch parameters, are a source of intelligence on foreign operations and are designation data sources for special space-object-identification (SOI) sensors. The present system is not adequate for the tasks of detecting objects at high altitudes nor for applications requiring guaranteed early detection. A DoD requirements document, JRDOD FY75-92, Jan. 25, 1973(S), specifies "detection to synchronous altitude by 1978 and 3 times synchronous altitude by 1991."

Only a small percentage of foreign launches are detected at present without a priori alerting information. In the case of Soviet test launches, geography constrains the trajectory to the east over the Asiatic land mass and the Pacific. Accordingly, an AN/FPS-17 and AN/FPS-79 intelligence-gathering radars were deployed in Diyarbakir, Turkey, and an AN/FPS-80

was located on Shemya, in the Aleutians, to monitor test shots. This equipment has been improved over the years and incorporated into the Spacetrack network. Additionally, intelligence sensors of the ionospheric forward-scatter type were deployed with propagation paths over the launch sites at Tyuratam and Kapustin Yar. These, along with the ELINT listening sites, gather countdown, liftoff, and telemetry information. Launches from Plesetsk are detected by the AN/FPS-92 BMEWS at Flyingdales, England, and were detected on an experimental basis by the AN/FPS-95, an HF monostatic over-the-horizon radar.

With the inputs from these sensors, few known Soviet space launches have occurred without good alerting information being available to the "detection" radars and WS-434. These few, including certain launches such as the FOBS, are not detected at present because they are EM-silent and are not in orbit over the longitude of any space-detection sensors. A new intelligence radar in the Far East will be tasked to help in certain circumstances. The first 49° inclination Cosmos satellites were detected without prior information on launch site and "nominal" orbital elements on the first pass through WS-434. The early French satellites launched from Algeria were detected without any alerting or "nominals" at the first system penetration. The first PRC satellites were detected on the first revolution as they over-flew CONUS, again without launch site or "nominals" information input to WS-434. Detections on new Japanese launches are routine, since NASA gives them extensive support.

The prime detection and cataloging sensors are the Naval Space Surveillance System, with headquarters at the Naval Weapons Laboratory, Dahlgren, Virginia (WS-434), and the FPS-85 radar at Eglin Air Force Base, Florida. They are connected via a high-speed data-transmission system, and the network is organized so that all uncorrelated (unknown) observations by WS-434 above 2000 n. mi. are handed off to the FPS-85 for tracking. In Ref. 1, NORAD states it has "programmed" the installation of new satellite tracking radars in South Korea for FY75, Samoa for FY76, and Ascension Island for FY76. The addition of these sensors would greatly improve system coverage and response, but will not improve high-altitude surveillance capability without sacrificing detection coverage.

The USAF Space and Missile Systems Organization (SAMSO) is managing an on-going space defense program, supported by

ARPA. One task of this program is called Space Track Augmentation. Space Track is the Air Force Space surveillance program, also supervised by SDC, and comprises orbital computation and SOI facilities at Colorado Springs, Baker-Nunn cameras, and several radars at other sites. This program investigates a ground-based effort using electro-optics and large radars, threat analysis/target definition/SOI studies and experiments, and a space-based effort using satellites with optical sensors. A forthcoming Mitre Corp. report on this subject will contain details, and should be distributed in the second quarter of FY74.

Thus it appears that except for various studies, little in actual equipment improvement is being done to upgrade the National Space Surveillance System to the level required to support active space-defense, high-altitude, antisatellite countermeasures and high-orbit instrusion detection.

ACTIVE SPACE DEFENSE

For space defense, the orbital elements generated by the space-surveillance system may be used in support of any future active antisatellite system (ASAT) which might be deployed. The elements are also used by the present antisatellite system based on Johnson Island, but NORAD's attitude (Ref. 1) is that this system is severely limited in capability.

Another area of interest is midcourse detection of ICBM's. The antiballistic missile is a long-standing NORAD requirement and has the highest priority in the R&D requirements documents (1,2). The two problems (ASAT and ABM) are quite similar, in that techniques of ground-based satellite surveillance are applicable to midcourse missile detection. An area of interest to NORAD, NAVSPASUR (Operators of WS-434), and Safeguard Systems Command (SSC) is the Anti-Submarine Launched Ballistic Missiles (ASLBM) and Anti-Fractional Orbital Bombardment System (AFOBS). There is interest at NORAD in employing WS-434 to designate the Safeguard missile system radars for objects launched from the Gulf of Mexico or de-orbited in this area, and NORAD has asked NAVSPASUR to study the feasibility. The WS-434 has recently demonstrated a capability to acquire the necessary data for this function. The AN/FPS-85 is being programmed to detect these objects, but with a resulting loss in cataloging and detection capability (9). Personnel from SSC Huntsville recently visited NRL to investigate the possibilities.

SUPPORT FOR ADVANCED MILITARY SPACE SYSTEMS PLANNING

This area of interest, and the one fueling an ARPA program at Lincoln Laboratory, is the LES-8, 9 project. The Lincoln Laboratory analysis of the high-altitude detection problem (10, 11) appears to be valid in defining limits of feasibility in unalerted detection of objects at synchronous altitude and above. One aspect of this problem is the importance of SDC's gap-filling program, because if continuous launch and injection data are available, the a priori limitations in the high unknown orbit are reduced to the point that radar detection may be more feasible. Any breakthrough in high-altitude detection will have great impact on the entire system concept.

PROTECTION OF CERTAIN STRATEGICALLY IMPORTANT SATELLITE SYSTEMS

The problem of high-orbit-intruder detection, of interest to DDR&E, requires high-altitude detection capability in a perimeter about a valuable and strategically important satellite to detect intruders that approach within approximately 2000 miles of the satellite. An optical sensor, FSR-X, long under development by RCA, has been tested, and an alternate radar approach is also being investigated by the same company. This area is one in which a threat could exist, since the Soviets have requested a frequency allocation for an equatorial "COMSAT" near the same longitude as the satellite of interest to DDR&E at this altitude. A similar radar and optical sensor could be used to monitor the orbit planes of Timation, for possible co-orbiting interceptors. A good capability to monitor the orbit of Timation may also be obtained by modest upgrading in capability of WS-434, as discussed in the Technical Addendum*. A ground-based (SOI) capability is desirable to add credence to the circumstantial evidence of the juxtaposition of a payload failure with a perimeter penetration. The use of on-board proximity and impact sensors may be added on certain payloads also (9, 12).

WS-434 Upgrading

Recently NRL was questioned by DDR&E about the feasibility of CW ground-based radar sensors for intrusion detection at synchronous altitude. Rough calculations were presented <u>informally</u> that indicated feasibility. This NRL exercise led

*The Technical Addendum is published separately as NRL Memorandum Report 2707A

to a reevaluation of proposals made in the past (13, 14, 15, 16), to improve the capability of WS-434.

Some recommendations were included in a funded program completed in early 1965, i.e., the conversion of the Naval Space Surveillance System WS-434 to a 216-MHz operating frequency from the original 108-MHz frequency. Other improvements were implemented (17). Since this time there has been no equipment upgrading or any other additions made to the system that had the effect of improving system detection capabilities, although a study into methods of increasing system traffic capacity was made (18). However, improvements in software at NAVSPASUR Headquarters, Dahlgren, Virginia are continuously in progress. The staff has improved the accuracy and timeliness of the orbital elements by incorporating the latest geodetic knowledge and orbital theory.

A range and velocity experiment, RVE (19), was funded and performed at R&D sites in south Texas, but it was not associated with the operational system in any way. The investment required to convert these sites to form an operational, parallel "fence" was not forthcoming, although the results of the RVE clearly indicated the advantages that would accrue in traffic-handling capacity and faster and more accurate orbit determination. However, the Eglin Field Spacetrack Radar (FPS-85) at about the same latitude has been completed and tied into the Naval Space Surveillance System with a high-speed digital data link for the interchange of data. This interchange has resulted in an operational doctrine which requires that all unidentified or unassociated objects detected by the Naval Space Surveillance system at altitudes about 2000 n. mi. will be handed off to the FPS-85 within five seconds in the form of a predicted look angle and range. FPS-85 power is thus conserved by leaving the difficult long-range surveillance functions to the WS-434. In practice, the data link works in only one way. Any FPS-85 output must go via the Space Defense System (SDC), Cheyenne Mountain, on its way to WS-434.

It was proposed to increase WS-434 capability (15, 16) by improving low-altitude coverage, so that a single-pass detection and orbit-computation capability would be obtained for essentially all orbits, launch azimuths, and launch points which could possibly represent a threat to CONUS. These proposals were not approved because the importance of the threat was not acknowledged (7), and the existing SPADATS system was deemed adequate. Not only was the WS-434 not

improved over the years, but also several sensors feeding to the Air Force SPADATS system and reporting to the SDC were closed down entirely.

The present detection situation is well illustrated by the case of 1972-72A, SDC 6192, a Soviet payload in a Molniya-type orbit. Its first pass over CONUS shortly after injection was near apogee (approximately 20,000 n. mi.), so that neither WS-434 nor any other SDC sensor has sufficient capability to detect it. The "low" pass penetrated WS-434 between CONUS and the Hawaiian Islands, and so was observed by only one WS-434 site, so according to SDC doctrine, was not reported to SDC. No other sensor was deployed appropriately for detection. This object remained undetected (simultaneous, two or more station observations) from injection on 19 September 1972 until 20 December 1972, when the high-pass altitude lowered to about 10,000 n. mi., and an orbit was computed from some single-station observations and several multiple-station detections. After several weeks this object precessed out of WS-434 coverage, and now must be essentially detected anew, since the orbital elements will have changed appreciably in the interim. (A special computer program including lunar-solar perturbation theory makes helpful predictions for redetections) Surveillance capability to synchronous altitude and a WS-434 receiving station in Hawaii would therefore have enabled WS-434 detection and orbit computation on this object after the first several passes.

An effective space-surveillance system is a closed loop. Observations are used to compute orbital elements, from which predicted observations are used to correlate with incoming raw detections. Inputs to this loop may include intelligence from external sources such as launch warning, alerting systems, and ephemeris from other sources. However, the system must be capable of bootstrapping itself from raw detections to a catalog of orbital elements. Hence it is convenient to study two separate functions: detection and data processing (including orbit computation, prediction, and cataloging). We consider only the detection function in the following discussion.

For credible surveillance in the context discussed here, an object the size of the Molniya communications satellite, which has been camouflaged to the maximum allowed by the state of art, so that the total backscattering cross section has been reduced by 10 dB, should be detectable with 90 percent probability. The present WS-434 system has been

observing various satellites at altitudes above 10,000 n. mi. on a regular basis. The Molniya communications satellites are particularly good test objects, because over a period of time they eventually penetrate the system at altitudes from several thousand miles to synchronous altitudes, making the probability of detection versus altitude statistics easy to collect. For example, observations of a set of 19 of these objects (3.4 m long and 1.6 m in diameter, Ref. 20, with large solar-cell panels and antennas) are shown in Fig. 1 for various penetration altitudes of the WS-434 up to 10,000 n. mi. Thus a measure of the capability of the operational WS-434 is a 50 percent probability of triangulation (P_T) with two or more observations per pass, of a Molniya class payload at 7500 n. mi. Therefore we can infer the increase in capability over the present operational WS-434 required to detect the postulated threat as follows:

Requirements	Gain Required (dB)
1. Increase range from 7500 n. mi. to 21,000	+18
2. Decrease cross section 10 dB	+10

This 28 dB increase in capability enables the threat to be detected and height and longitude measured 50 percent of the time. To increase probability of detection (P_D) the sensitivity must be increased further. The requirements can be calculated, using the discovery made at NRL in 1960 from analysis of data from the then-evolving WS-434, that the apparent back-scatter cross section of satellites is distributed log-normally (21, 22), and that irregularly shaped objects such as cylinders with protuberances have a cross-section distribution with a 6-dB standard deviation. Using this distribution with the above 28-dB gain and a required 90 percent probability of detection, the same object may be seen at only

$$\frac{21,000}{1.0/0.65} = 13,700 \text{ n. mi.}$$

To detect this object at 21,000 n. mi. with P_T = 90 percent therefore requires

$$10 \log \left(\frac{21,000}{13,700}\right)^4 = 10 \log 5.52 = 7.4 \text{ dB}$$

more capability, or a total of 28 + 7.4 = 35.4 dB increase over the present system, assuming an equivalent single receiving site. Systems using multiple receivers such as WS-434 increase P_T without actually requiring increased single-station capability however.

In the Technical Addendum, the feasibility of physically realizing this increase in system capability and its cost is studied. It is probably not cost-effective to increase transmitter power and antenna length much over the 1.0-megawatt average and two-mile antenna length presently employed in WS-434 at least initially. However, since none of the receiving antennas are two miles long, at some sites it may be feasible to lengthen the antennas up to this limit. Likewise, the ultimate in integration time, and hence detection sensitivity, has not been incorporated, so that for certain classes of satellites gains are available in this area. Gains can be achieved economically by reducing receiving-system noise figure. The addition of new receiving stations also improves detection probability and, more importantly, such additions increase height measurement accuracy and coverage.

In the addendum a multiphase program is proposed to gradually acquire this required capability, as summarized in the following paragraphs.

1. The most effective first step in increasing WS-434 capability on high-altitude objects is the installation of new detection equipment (preselectors) and associated electronics with greater sensitivity than the existing equipment. For example, the improvement per receiving station for the orbits studied in the Technical Addendum are:

- 9 dB improvement with Timation III type objects
- 13 dB improvement with Molniya type objects
- 21 dB improvement with OgoI and Prognoz type objects.

This capability costs an estimated $0.750M per station.

2. Three stations so upgraded with funds for a limited capability receiving station on Maui, Hawaii, will enable the height, time, and longitudes of system penetration to be determined on Timation III 65 percent of the time (21 percent of the time on the Timation III apogee motor) for a capital investment of about $4.75M. From knowledge of station location and antenna patterns, and the data of Fig. 1, a vertical coverage pattern for the present system can be inferred, as

shown in Fig. 2. Also shown is the increased coverage obtained by adding the new preselectors at all sites, and a receiving site at Maui, Hawaii, and equipping two "short range" receiving sites with antenna systems similar to those presently installed at two long-range sites.

The next increment in capability increase involves lengthening the alert antenna to the maximum of two miles and lengthening the phase-meter antennas. This step would increase the capability of a single station by 3.5 dB. This capability can be increased by another 3 dB by adding two other alert antennas with half the EW beamwidth, partial preselectors, and long phase-meter antennas, at a cost for the initial upgrading of $3.5M per station (the additional 3 dB increment also costs $3.5M. The added 6.5 dB gain at four sites (it appears that the real estate situation precludes the two-mile-long antennas at Maui, Hawaii, Ft. Stewart, Ga, and San Diego, Cal, SS) will give the capability shown on Fig. 2, i.e., a 90 percent probability of triangulation of Molniya type payloads at apogee over CONUS.

It is technically feasible, with recent developments in high-power vacuum tubes, to increase transmitter power by 10 dB so that objects as small as 1 m^2 could be observed 90 percent of the time over CONUS.

CONCLUSIONS

WS-434 can be improved in high-altitude detection sensitivity, and in low-altitude and longitude coverage to improve its surveillance capability for data collection and orbit computation. The easiest improvement is that of improving the high-altitude coverage as discussed in the technical addendum. Such improvement would be of great value to the Timation program, since it would allow reliable and accurate calculation of the orbital parameters and apogee motor separation.

High-altitude capability for intruder detection in a perimeter about certain expensive, strategically vital satellites is a problem being funded by DDR&E and being investigated by RCA, using optical and radar techniques. The Navy has satellite systems in being and planned requring the same protection. Identification and orbit monitoring are vital additional functions required, in addition to simple detection, before a satellite-system failure can positively be assessed as accidental or "on-purpose", hence the sudden resurgence of interest in SOI.

The designation of Safeguard missile site radars by the Naval Space Surveillance System against objects approaching the United States from the south (SLBM, FOBS) is feasible and should be pursued.

RECOMMENDATIONS

It is recommended that work be done to study in more detail (a) the possibility of using the RCA-developed techniques for perimeter protection of certain high-altitude Navy satellites, (b) orbit monitoring and SOI techniques for protection of subsynchronous Navy satellites by profiling and precision velocity measurement of co-orbiting intercepter vehicles and protected spacecraft, and (c) WS-434 potential for higher altitude detection.

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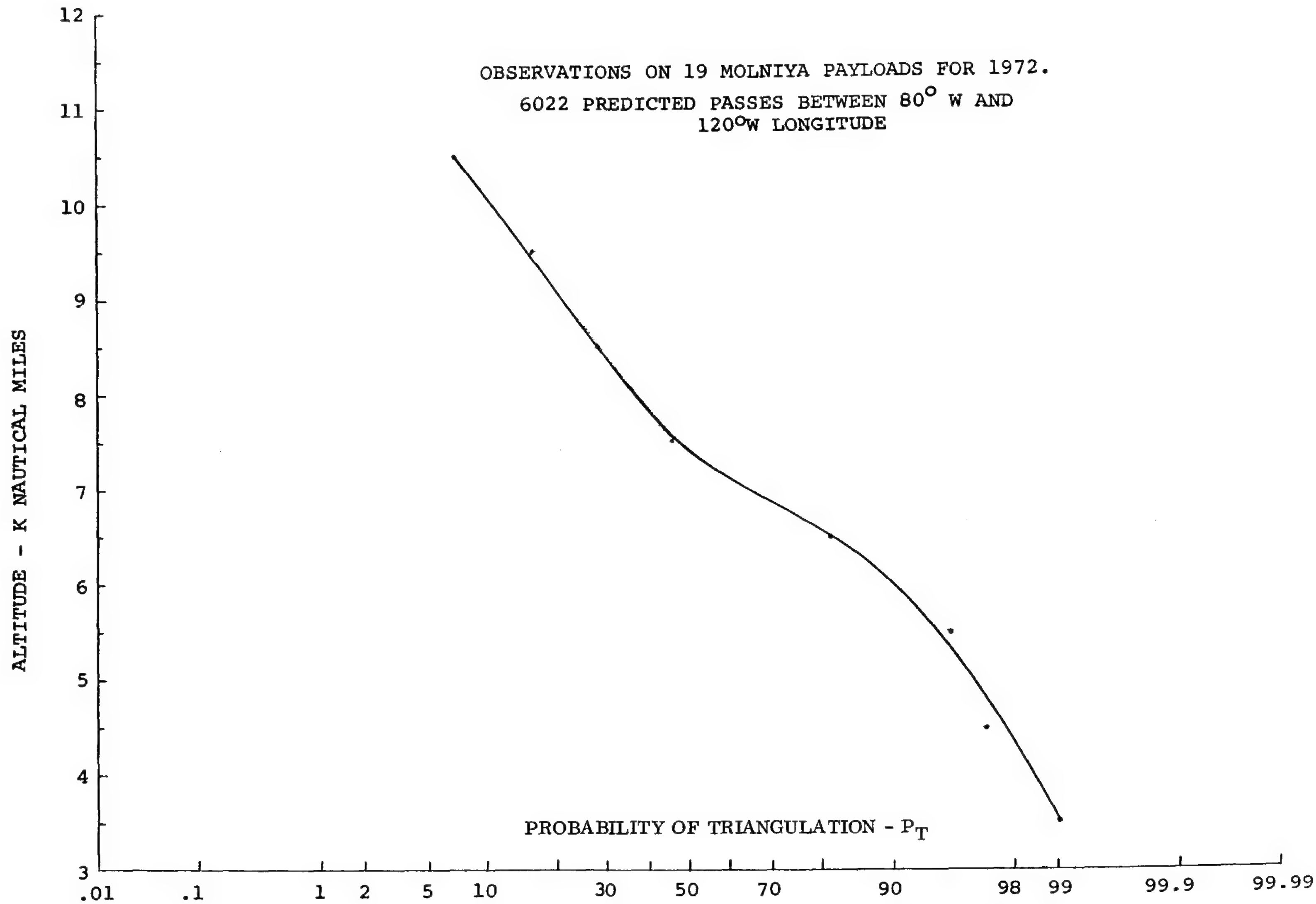

Fig. 1 - Probability of triangulation (P_T) vs altitude

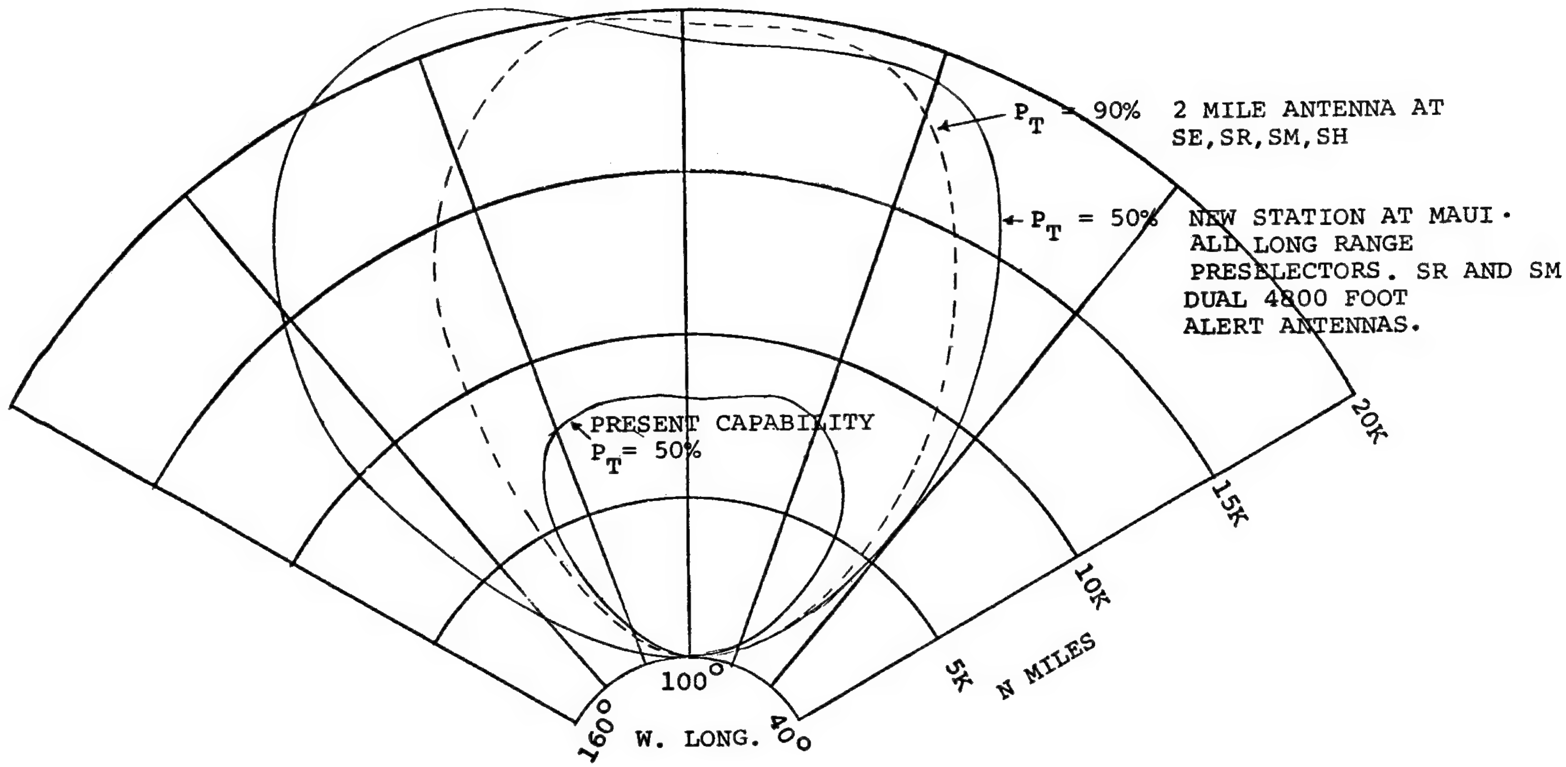

Fig. 2 - Coverage for Molniya -type payloads

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Technical Addendum
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SUMMARY

Factors affecting system sensitivity in WS-434 are identified, and system parameters chosen accordingly to maximized range capability. A progressive development plan is then developed which provides an evolving capability with funding requirements. It is shown that WS-434 can be upgraded, so that it will acquire the capability of detecting and locating objects of 10 m^2 cross section penetrating the system from 40 to 160°W longitude at synchronous altitudes with 90 percent reliability for approximately $44M. A new transmitter costing an additional $30M enables the same capability on 1.0 m^2 objects.

INTRODUCTION

The present WS-434 was designed to detect both high and low altitude objects, and hence it represents a compromise in such factors as sensitivity, low-altitude coverage, and capacity. This compromise eventually translates into a design choice specifying system noise bandwidth, which is therefore sub-optimum for maximum sensitivity and hence range capability. The philosophy adopted in this proposal is to redesign, modify, or otherwise disturb the operational system as little as possible, but to add in parallel auxiliary long-range detection equipment (preselectors), phasemeters, and data-processing equipment to reduce system noise bandwidth to match more closely the parameters of objects of 10 m^2 area or larger at synchronous altitudes. A second phase of the program would involve adding to the existing antenna systems length and reducing east-west beamwidth (to increase gain on the high targets) at the present short-range receiving stations. They will then be configured similarly to the present long-range stations. The third phase would involve lengthening the antennas to the maximum of two miles at four receiving sites. Only if it is required that objects as small as 1 m^2 cross section be observed at synchronous altitudes with a two or more station probability of detection of 90 percent would it be necessary to upgrade the system transmitter.

In order to design the "long-range preselector," certain characteristics of the echo return from distant objects (>7500 n. mi. range) must be considered. These parameters will determine the integration time available for reducing minimum detectable signal level. The most important parameter is the maximum doppler shift to be encountered which specifies the surveillance band. The parameter second in importance is the time-in-beam, that is, the length of time the satellite is illuminated by the transmitter, which determines receiver I-F and postdetection bandwidths. The rate of change of doppler will be a factor in determining the minimum receiver I-F bandwidths. All these parameters are determined by the orbital elements of the object, and the system frequency. The latter factor is specified when considering an upgrading of the existing WS-434. In addition, the target shape and motion will determine minimum receiver I-F and postdetection bandwidth.

EFFECT OF ORBIT ON SYSTEM PARAMETERS

Doppler Shift

The angular velocity of a satellite is the starting parameter for calculating relative velocity between the satellite and an observer. For a circular orbit (eccentricity = 0), the angular velocity is given simply by

$$\dot{\theta} = \frac{2\pi}{T} \tag{1}$$

where T is the period. In the more likely case of an elliptical orbit (Fig. A1), where eccentricity is not zero but lies between zero and one, the instantaneous angular velocity is a function of the mean velocity and the eccentricity. From Kepler's law of constant area,

$$\frac{\dot{\theta} r^2}{2} = \frac{\pi a^2 \sqrt{1 - e^2}}{T} \tag{2}$$

where r = radial distance from the center
a = semimajor axis (in earth radii)
e = eccentricity.

$$r = \frac{a(1 - e^2)}{1 + e \cos \Theta} \text{ for an ellipse} \tag{3}$$

$$\dot{\Theta} = \frac{2\pi a^2 \sqrt{1 - e^2}\,(1 + e \cos \Theta)^2}{Ta^2\,(1 - e^2)^2} \tag{4}$$

$$\dot{\Theta} = \frac{2\pi(1 + e \cos \Theta)^2}{T(1 - e^2)^{3/2}}$$

$$\dot{\Theta} = K\dot{m} \text{ where } \quad K = \frac{(1 + e \cos \Theta)^2}{(1 - e^2)^{3/2}} \text{ and } \dot{m} = \frac{2\pi}{T} \tag{5}$$

Equation (3) gives the radial distance. Radial velocity is determined by differentiating the radial distance

$$\dot{r} = \frac{re \sin \Theta\, K\dot{m}}{(1 + e \cos \Theta)^2} \tag{6}$$

Figure A2 shows the ground track of a typical satellite as it intersects the WS-434 fence great circle. The arc h from the observer o to the subsatellite point of passage P can be calculated using the familiar navigator's equation

$$\cos h = \sin Lat_o + \cos Lat \cos Lat_o \cos LHA \tag{7}$$

where LHA is the difference of longitude between the observer and the subsatellite point; it is called in navigation the Local Hour Angle. The longitude of the fence crossing is assumed. Latitude is calculated from spherical trigonometry. The arcs b_s and c_s are expressed in terms of latitude of crossing and the satellite inclination I:

$$c_s = \text{arc sin } (\sin Lat/\sin I) \tag{8}$$

$$b_s = \text{arc sin } (\tan \text{Lat}/\tan I) \tag{9}$$

$$\text{Lat} = \frac{\sin I \cos c_s K\dot{m}}{\cos \text{Lat}} \tag{10}$$

$$\text{LHA} = \frac{\cos I \cos^2 b_s K}{\cos^2 c_s} - \left[\frac{a^{3/2}}{17.0436}\right]\dot{m} \tag{11}$$

The second term inside the bracket accounts for earth rotation. The first term gives east-west motion over a stationary earth.

The range d from observer to the satellite is given by the law of cosine:

$$d = \sqrt{r^2 + 1 - 2r \cos h} \text{ (see Fig. A3).} \tag{12}$$

Equation 7 is differentiated to yield:

$$\sin h\dot{h} = \cos \text{Lat}_o (\cos \text{Lat} \sin \text{LHA} (\dot{\text{LHA}}) + \sin \text{Lat} \cos \text{LHA Lat})$$
$$- \cos \text{Lat} \sin \text{Lat}_o \dot{a} \tag{13}$$

Equation 12 is differentiated to give

$$\dot{d} = \frac{r \sin h\dot{h} + (r - \cos h) \dot{r}}{d} .$$

To this point, the result is in terms of $\dot{m}$ and earth radius R.

Where $$\dot{m} = \frac{2\pi(17.0436)}{a^{3/2} \ 86400} \frac{\text{radians}}{\text{second}} \tag{15}$$

$$R = 6378 \text{ km} \tag{16}$$

$$\text{Therefore:} \quad \text{Doppler} = \frac{f_o \, R\dot{d}}{\text{Velocity of light}} \tag{17}$$

For ease of calculation, the various equations were programmed into a Hewlett Packard 9100B desk calculator, with intermediate results stored in memory. This procedure allowed flexibility in choosing satellite parameters.

Several representative orbits from the WS-434 catalogue were calculated.

Satellite	a	e	I	Argument of Perigee
Timation III	3.18	0.01	125°	280°
Molniya (6356)	4.16	0.737	65.2°	286°
Prognoz	16.715	0.9358	64.9°	295°
1969 49A (OGO-1)	12.736	0.357	58.8°	006°

Dopplers were calculated for the transmitter at Lake Kickapoo, Texas, and the receiver at Fort Stewart, Georgia. In addition, a receiver was assumed on the island of Maui in the state of Hawaii. The results are plotted in Figs. A5, A6, A11, A12, A19, A20, A25, and A27.

Time in Beam

Referring to Fig. A2, the angle B_f is determined from fence parameters:

$$\sin B_f = \cos A / \cos \text{Lat} \tag{18}$$

The angle B_s is determined from the angular velocity components of the satellite as:

$$\tan B_s = \text{LHA}/\dot{\text{Lat}} \quad \text{and} \tag{19}$$

$\alpha = 180^\circ - B_s - B_f$ = angle between the satellite path and the fence plane.

The distance traveled in the fence is the fence thickness divided by the sine of angle α. The fence thickness is range times the included angle in radians. In the far field, the antenna at the transmitter station generates a beam that is 1/40 degree between the half-power points. The velocity of the satellite through the beam is calculated from the components $\dot{LHA}$ and $\dot{Lat}$:

$$v = r\sqrt{\dot{LHA}^2 + \dot{Lat}^2} \tag{21}$$

$$\tau = \text{time in beam} = \frac{\frac{\pi R}{7200}\sin\alpha}{v}\ \text{sec} \tag{22}$$

All of the necessary numbers were stored in the calculator memory while the doppler shift was being calculated. An additional short program yielded the data shown in Figs. A4, A9, A17 and A23. Shown on Figs. A10, A18 and A26 is the variation in altitude at system penetration for the last three payloads (Timation III nominal orbit is circular at 7500 n. mi. altitude) in order to visualize the ranges involved.

Rate of Doppler Shift

The rate of change of doppler shift is proportional to the second derivative of distance:

$$\dot{d} = \frac{(r - \cos h)\dot{r} + r\sin h\dot{h}}{d} \tag{23}$$

$$\dot{d} = \frac{r(\sin h\ddot{h} + \cos h\dot{h}^2) + (r - \cos h)\dot{r} + 2\sin h\dot{h}\dot{r} + r^2 - d^2}{d} \tag{24}$$

The quantity $(\sin h\ddot{h} + \cos h\dot{h}^2)$ in the first term is the derivative of $\sin h\dot{h}$. Recalling Eq. (13),

$$\sin h \dot{h} = \cos Lat_o (\cos Lat \sin LHA (\dot{LHA}) + \sin Lat \cos LHA \dot{Lat})$$

$$- \cos Lat \sin Lat_o \dot{Lat} \qquad (25)$$

Differentiating both sides with respect to time,

$$(\sin h \ddot{h} + \cos h \dot{h}^2) = \cos Lat_o \cos Lat \sin LHA (\ddot{LHA})$$

$$+ \cos Lat_o \sin Lat \cos LHA - \sin Lat_o \cos Lat) \ddot{Lat}$$

$$+ \cos Lat_o \cos Lat \cos LHA (\dot{LHA})^2$$

$$+ \cos Lat_o \cos Lat \cos LHA + \sin Lat_o \sin Lat)(\dot{Lat})^2$$

$$- 2 \cos Lat_o \sin Lat \sin LHA (\dot{LHA}) \dot{Lat}). \qquad (26)$$

The necessary second derivatives are found by differentiating previously used first derivatives,

$$\ddot{LHA} = \frac{(\dot{LHA} + 1) \dot{K}}{K} \qquad (27)$$

$$\ddot{Lat} = \frac{\dot{Lat} \dot{K}}{K} \qquad (28)$$

$$K = \frac{-2e \sin \theta K \dot{\theta}}{(1 + e \cos \theta)} \qquad (29)$$

The calculation of doppler rate, using the intermediate stored results, is a lengthy but straightforward operation. The results are plotted for the satellites of interest in Figures. A7, A8, A13, A14, A15, A16, A21, and A22.

Body Motion and Frequency Stability Limitations on Integration Time

It is well known that if a satellite of effective length L ft is rotating normal to the illumination of frequency f_o at a rate f, then the received echo will be spread in a band of width:

$$fd = \frac{4\pi}{c} Lff_o \text{ in Hertz}$$

or at the system frequency f_o of WS-434 of 216 MHz,

$$fd = 2.77Lf.$$

Thus for a preselector resolution of 20 Hz, and a 10-ft-long satellite, body rotation must be less than

$$f = \frac{20}{27.7} \approx 0.6 \text{ Hz}$$

to avoid signal power loss. There is an additional loss of signal power if the low-pass filter-integrator is narrower than 0.3 Hz in this example. Since most objects of military interest are stabilized, this condition is fulfilled.

Integration times of 125 sec or more also impose rather more stringent frequency-stability requirements on the system transmitter and local oscillators than is now the case in WS-434. Thus for

$$f_o = 2 \times 10^8 \ H_z,$$

$$\frac{\Delta f_o}{f_o} = \frac{1}{f_o \Delta T} = \frac{1}{(2x10^8)(125)} = \frac{1}{250x10^8} = 4x10^{-10}$$

is required at the transmitter and the first local oscillator stages, which is achievable with the present state of the art.

FACTORS DETERMINING SYSTEM SENSITIVITY

Preselector Parameters

The WS-434 system bandwidth, and hence sensitivity, is determined by the detection or alerting system called the preselector, which is an array of crystal filters, threshold detectors, and integrators. At present, WS-434 employs three types of preselectors: 100-Hz filters with 17- and 300-millisec integrators at San Diego and Silver Lake, a 100-Hz unit at Ft. Stewart with a 95-millisec time constant, and units with 50-Hz filters and 95-millisec time constants at the other sites. The variations in values are due to the evolutionary way the system was deployed. The later units, installed when system frequency was changed to 216 Mc and when a two-mile-long transmitting antenna was added, are based on the assumption that most objects are within the near field of the transmitting antenna (i.e., objects lower than approximately 5000 n. mi.). For this study we wish to design detection equipment for objects above this region, and so must first determine the expected doppler band in order to decide how many channels of a particular bandwidth are required and, from the expected time in the transmitter antenna beam, determine the time constant of the postdetection integration. The preceding paragraphs develop the expressions for these parameters versus the orbital parameters of four representative objects. These values are plotted versus longitude of the system penetration in Figs. A4 to A29. From these curves it can be seen that a doppler band of 8 kHz is necessary (although it is possible to postulate objects with high apogees and eccentricities with higher dopplers, Fig. A30). From these curves we also observe that these objects can be illuminated for periods τ of from 5 sec to over 500 sec when above 5000 n. mi.

An estimate of the increase in system sensitivity available can then be made* from Fig. A31 with bandwidth per channel and postdetection bandwidth PDBW ($W = 1/2\tau$) as parameters with constant threshold S/N (false-alarm rate, FAR). Thus a tradeoff can be made between cost (proportional to filter bandwidth or number of channels for a constant doppler band) and sensitivity. A background noise temperature of

*R.R. Zirm, "Optimizing of Range Capability in the U.S. Navy Space Surveillance System," NRL Report 5621, (Secret) Aug. 21 1961

$1000^{\circ}K$ (an approximate minimum value observed by WS-434, Fig. A32), and a threshold S/N of about 20 (for FAR of about 10 per hour, Fig. A33) is assumed. Table A1 shows the expected gain in sensitivity using a "long-range" preselector with three postdetection bandwidths to accommodate the typical orbits discussed previously, and three typical filter bandwidths. It is seen that gain in sensitivity due to narrower filters is extremely expensive; i.e., a preselector with five times as many channels (10 Hz vs 50 Hz) obtains a gain in sensitivity of only 1.5 dB for objects in the system for a period of several seconds, to about 3 dB for the infrequent case of an object in the beam several hundred seconds. On the other hand, it would be costly to add 3 dB in increased transmitter capability, and the cost of larger receiving antennas may be excessive.

Reducing System Noise Temperature

Another area where an increase in system capability could be bought cheaply part of the time is in low-noise receivers. The existing system uses first-generation transistor preamps with noise figures of about 3 dB. A recent investigation with several manufacturers indicates that noise figures in the region of 1.5 dB for a narrow band around 216 Mc is feasible, and might cost in the region of $1000 each in quantities of about 100 units. An uncooled preamp with 0.5 dB noise figure is commercially available for about $5K. The gains in sensitivity that might be achieved <u>during quiet</u> periods are shown in Fig. A34* when compared

*In Radiation Laboratory series Vol. 24, Lawson and Uhlenbeck state that sensitivity S of a receiver which is proportional to its output S/N is

$$\frac{1}{F - 1 + (T/T_O)}$$

where F is the receiver noise figure
T_S is the sky temperature
T_O is room temperature = 288°
but receiver noise figure is

$$1 - \frac{T_r}{T_O}$$

where T_r is receiver noise temperature, so that

$$S = \frac{1}{(T_r/T_O) + (T/T_O)} = \frac{T_O}{T_r + T_S}$$

with the present 3 dB system with a minimum sky temperature of 1000°K and a seasonal variation as shown in Fig. A32. Thus 1 dB gain or less is usually achievable, 2 dB probably 2 percent of the time, and 6 dB on even rarer occasions.

Increasing Antenna Gain

Since the transmitting antenna is two miles long, the gains of the detection antennas at the receiving sites may be increased by lengthening them to two miles if geography and real estate permit.) The alert antennas at the short-range stations at Ft. Stewart, Ga. (SF), Silver Lake, Mississippi (SM), Red River, Ark. (SR), and San Diego, Calif. (S), are 1600 ft in length, so a gain of 10 log (10,560/1600) = 8.8 dB is possible in principle. If a new, separate alert antenna is built for long-range operation only, its EW beamwidth may be restricted somewhat (this also reduces direct feedthrough from the transmitter) so that 10dB gain should be achieved. If two closely spaced arrays are constructed with two separate preselectors (as is done at the long-range sites at Elephant Butte and Hawkinsville), 13-dB gain may be achieved. The gains at the long-range sites - Elephant Butte, New Mexico (SE) and Hawkinsville, Ga. (SA) would be 10 log (10,560/4800) = 3 dB, or 4.5 dB with restricted EW beamwidth. A WS-434 upgrading plan would balance the costs of these antenna improvements with the preselector costs. The phase-measuring antenna lengths and interferometer baselines, must be increased proportionally also to acquire good angle data at the increased height.

Effect of Number of Receiving Stations

System sensitivity and range capability as a function of the probability of detection (P_D) for satellites was discovered at NRL in 1960 to be log normally distributed, as shown on Fig. A35. System gain can be achieved by adding more receiving sites. If these sites are geographically separated along the system geodesic, longitude coverage is also improved. For example, consider the two long-range sites at SE and SH and a third site of equivalent capability at Maui, Hawaii. The binomial distribution enables one to calculate probability that at least one station with probability of detection (P_D) observes the object as follows:

* Figure A34 is plotted for $T_O = 288^{\circ}$K, $T_s = 1000^{\circ}$K, $T_r = 288^{\circ}$K (3 dB), or $S = \frac{288}{4288} = 0.065$ normalized as 0 dB.

$P_{O1} = P_D^{\ 3}$ = (probability that all three stations detect)

$P_{O2} = 3P_D^{\ 2}\ (1 - P_D)$ (probability that two out of three stations detect)

$P_{O3} = 3P_D\ (1 - P_D)^2$ (probability that one out of three stations detect)

$P_{O4} = (1 - P_D)^3$ (probability that no stations detect target).

This function is plotted in Fig. A36 as the sum of the first three terms (the cases of 2, 4, 5, and 6 stations are also plotted), where it can be seen that for P_D = 50 percent, there is an 85 percent probability of one of these stations detecting it. Using Fig. A35 for a target whose mean cross section is log-normally distributed with a 6 dB standard deviation, one can calculate trade-offs between system gains and loss, range capability, and probability of detection. For this example the increase in probability that at least one station will detect the object from 50 percent to 85 percent can be seen as equivalent to a sensitivity (or transmitter power) increase equal to the inverse fourth power of the corresponding normalized range, i.e. $(1.0/0.7)^4 = 4$ or 6 dB. Of course, to measure height and longitude in addition to simple detection, at least two sites must detect the satellite; a triangulation probability (P_T) for three stations is then 50 percent, because the P_{O3} term can no longer be added in. If some additional sites were upgraded, this gain will increase, as shown in Fig. A37, until for example five sites are used. A P_D of 50 percent then yields a system P_T = 82 percent.

RECOMMENDED WS-434 UPGRADING PROGRAM

Upgrading of the WS-434 program is recommended in evolutionary steps, starting with the R&D on an improved preselector and a survey of the state of the art, and advances made since 1964. A few critical circuits were tested to realistically assess costs. Next a partial unit will be designed and constructed. This unit will be expanded and installed at the "long-range station" at Elephant Butte (SE) for test and, hopefully, will be available for the Timation III satellite launch. Since we have shown earlier that a

doppler band of at least ± 4 kHz is required for most targets of interest, a 400-channel unit is recommended with 20-Hz filter bandwidths. The previous results show that the rate of change of doppler is small enough to be contained by a 20-Hz filter for the integration time required. The gains achievable on Timation III, for example, are (Fig. A4): the minimum detection time is limited to about 2.5 sec (the remaining 2.5 sec are required to measure angle of arrival) or a 3 dB postdetection bandwidth (P_D) of 1/2(2.5) = 0.200 Hz. From Fig. A31, we find the minimum usable signal (MUS) to be -155.2 dBm, while the operational preselector (50 Hz filter bandwidth) has a MUS with a P_D of 1.67 Hz, ($1/2\pi RC$) of -147 dBm, or a gain of 7.5 dB. In addition previously shown results indicate that with low-noise preamps another 1.5 dB in sensitivity may be attained perhaps 10 percent of the time. It is estimated* that the present WS-434 has a P_T of 50 percent and a P_D at SE of 30 percent on Timation III. Using the log-normal distribution with 6 dB SD (Fig. A35), it is found that a 7.5-dB increase in sensitivity increase P_D from 30 percent to 75 percent. This improvement indicates that the possibility of observing the apogee kick motor is increased to the point that it will be observed occasionally (if its cross section is 1/6 the satellite, P_D would be 30 percent with the 7.5 dB improvement).

The cost of equipment procurement is estimated as:

Preselector	\$600K
Auxiliary electronics (receivers, phasemeters, data processing, etc.	\$150K
Total	\$750K

This equipment could be constructed and deployed one year after go-ahead.

Similar equipment could be installed at the long-range stations in Hawkinsville, GA, (SH). This would enable height and longitude measurement on some passes of Timation III to be made, so that orbital elements could eventually be calculated.

*R. R. Zirm and R. Brescia, "Detection of TIMATION III, Space Applications Branch, TIMATION Memo #55, 29 Jan. 1971

The next increment could be the addition of a receiving site at Maui, Hawaii, using a limited-coverage antenna (approximately 90° EW required looking eastward) which would greatly improve P_D, P_T and longitude coverage, and expedite initial orbit computation. A limited-capability site might be procured for $3.25M. The electronics costs would be about the same as that of the other sites. In summary, a three-station complex of this type would cost:

1.	SE	$0.750M
2.	SH	$0.750M
3.	Maui	$3.250M
	Total	$4.750M

An additional 0.250M is required for data transmission and processing. The entire program could be accomplished in three years, after go-ahead. The expected capability against the Timation III apogee motor would be about 65 percent system P_D and 21 percent P_T (see Figs. A35, A36), good enough to calculate an orbit after a reasonable time.

WS-434 is the only sensor with a real-time unalerted detection capability on the Molniya communication satellites* in the SPADATS system. Figure A38, taken from this reference, indicates a P_T of 50 percent at 7500 n. mi. on these objects; however, satellites in slightly different orbits are seen only occasionally or not at all for extended periods. Figure A9 shows that the high passes (North-South) are seen for as long as 25 seconds for this particular object. Slight variations in the orbit will increase or decrease this (and change heights, in this example 14,000 n. mi., to a maximum of 21,000 n. mi.). Assuming then a "nominal" Molniya at 21,000 n. mi., it will be seen for 30 seconds or so. This specifies a detector integration time of 15 seconds. Angle-of-arrival data will be acquired during the remaining 15 seconds. Thus a preselector postdetection bandwidth of $\tau = 1/2(15) = 0.03$ Hz is required. The resulting detection sensitivity (Table A1 with 20-Hz filters) is -160 dBm, or a gain of approximately 13 db over the present sensitivity.

From the observed capability on these objects, Fig. A38, $10 \log (21{,}000/7500)^4 = 18$ dB, or 5 dB additional gain is

*NAVSPASUR letter V22:PMF;msc 3163 ser 203 Apr 25, 1973 "Preliminary Results in Requested High Altitude Analyses"

required for the same performance at 21,000 n. mi. (P_T = 50 percent). The additional gain can be achieved by (I) adding dual 4800-ft-long alert antennas and longer interferometer antennas at the short-range sites at Silver Lake, Mississippi (SM), and Red River, Arkansas (SR), which presently have single 1600-ft-long alert antennas. (The real estate situation at Ft. Stewart, Ga. (SF) and San Diego (SS) precludes further antenna deployment.) This gain is 10 log 2(4800)/1600 = +7.8 dB, or a total of 13 + 7.8 = 21 dB. From the known antenna patterns, the coverage resulting from these improvements is shown in Fig. A39. The additional site at Maui compensates for not upgrading SS or SF (also we have increased the antenna gains at SR and SM by 7.8 dB instead of 5 dB). The cost of this program is estimated below.

Long-range preselectors at SS, SM, SR, and SR,		4x0.75M = 3.0M
Dual alert and lengthened interferometer antennas at SM and SR		2x4.0M = 8.00M
	Total	11.00M

Two other examples were investigated previously - 1972-29A, Prognoz and 1964-54A OGO-1. The former object is particularly interesting, because no U.S. orbits exist; it cannot at present be detected by any U.S. sensor even if its argument of perigee were to bring it over CONUS. Both objects could be seen for 50 to over 500 seconds, and the doppler shift is within the postulated ± 4 kHz. For 150 seconds time-in-beam, for example, a postdetection bandwidth of 0.003 Hz could profitably be used for a MUS of -166 dBm, or a gain of 20 dB over the present capability. For certain conditions, integration times even greater might be feasible.

The next increment in system improvement involves lengthening the antennas at SM, SH, SR, and SE (the real estate situation precludes additions at SF, SS, and Maui) to the limit of two miles. This step requires the dual alert antenna lengths to be increased from 4800 ft to two miles, for a gain of 3.4 dB, and halving the east-west beamwidth of all four antennas so that another pair of two-mile alert antennas may be deployed for an additional 3 dB gain. Of course two additional partial-coverage preselectors must be added, and phasemeter antenna lengths must be increased to two miles. This addition improves the P_T of Molniya type payloads over CONUS to approximately 90 percent, as shown in Fig. A39. The cost is estimated as

Increasing antenna length, \$6M/station x 4 stations	\$24M
Four dual partial coverage preselectors and electronics, 4x \$1.0M	\$ 4M
	\$28M

To accomplish the detection of the original postulated threat of a reduced-cross-section Molniya sized payload, discussed in the report, requires an additional 10 dB system gain, which can be obtained only by increasing transmitter power. This change is technically feasible and requires rebuilding the transmitting station using new high-power-output transmitting tubes of 500 kW output rating, replacing the present 50-kW units, and increasing the power-handling capabilities of the antenna. This capability also allows the detection of OGO-Prognoz type payloads to over twice synchronous altitudes. This great transmitter (by far the largest in cw output) will cost about \$30M. The total cost to counter the threat postulated, i.e., a 1.0 m^2 cross section object at synchronous altitude with a P_T = 90 percent, is then

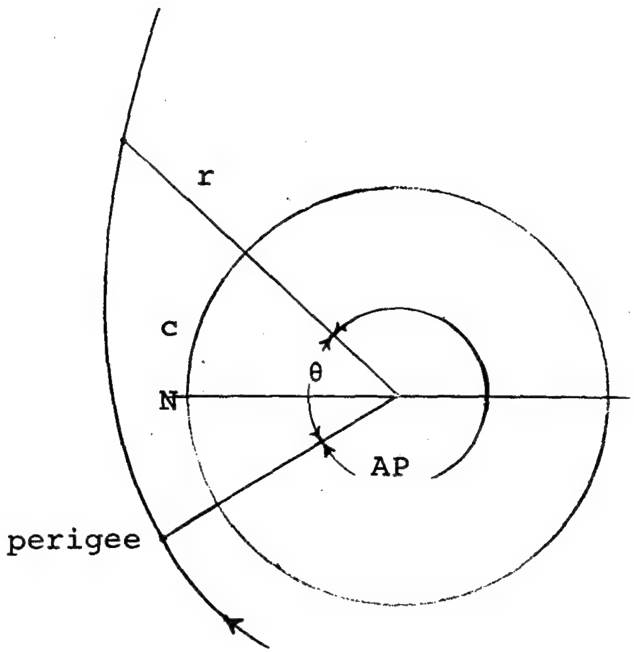
Phase I (see page 14)	\$5.0M
Phase II (see page 15)	\$11.0M
Phase III (see page 16)	\$28.0M
New Transmitter	\$30.0M
Total	\$74.0M

Table AI (U)

PRESELECTOR SENSITIVITY IMPROVEMENT (dB)

Preselector Type	W (Hz)→	B = 50 Hz			B = 20 Hz			B = 10 Hz		
		0.3	0.03	0.003	0.3	0.03	0.003	0.3	0.03	0.003
	P (dBm)	152.3	159	164	153.5	160	166	154	161	167
B = 100 Hz "ITEK"	149	3.5	10	15	4.5	11	17	5	12	18
100 Hz "NEW"	147	5.5	12	17	6.5	13	19	7	14	20
50 Hz "NEW"	147.5	5.0	11	16.5	6.0	12.5	18.5	6.5	13.5	19.5

FAR = 10/hr., $T = 10^{3\,\circ}K$



$\theta = c - AP$
IF $\theta \geq 180^\circ$ subtract 360°

Fig. A1 - Angles and distances in the plane of the orbit

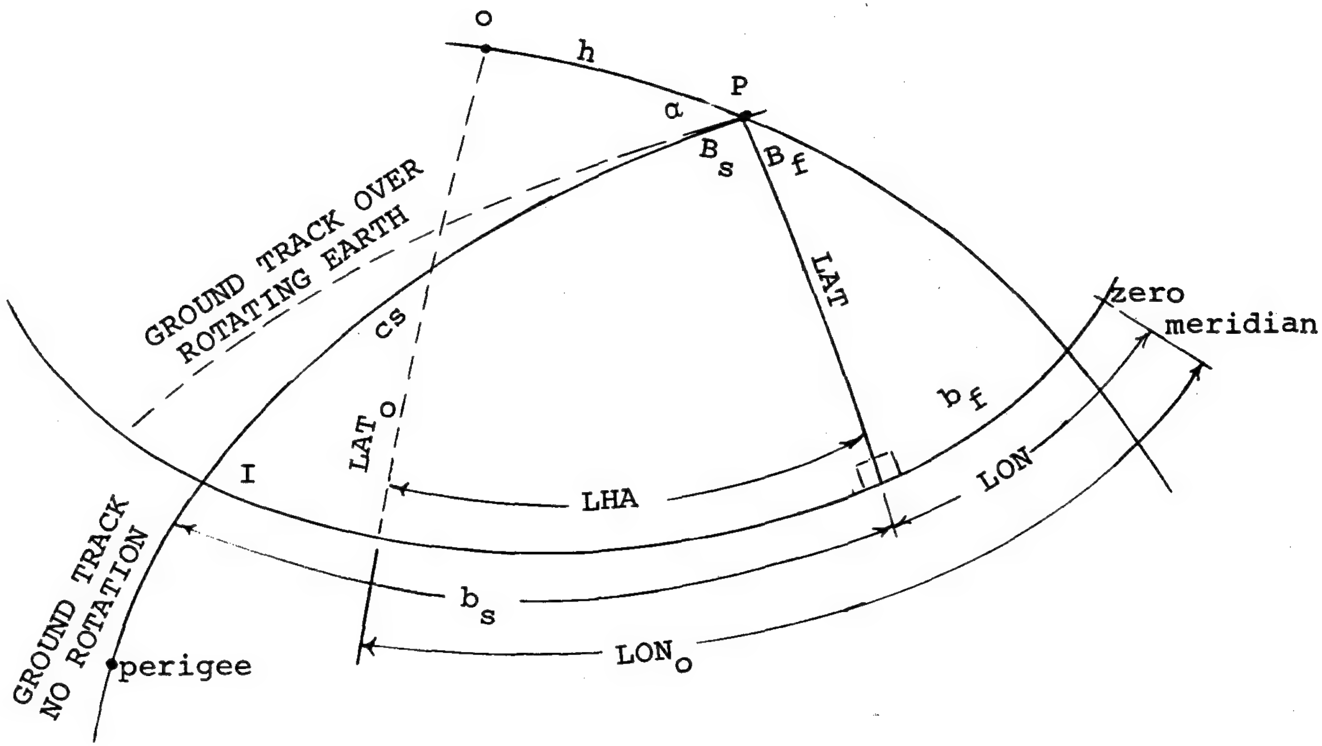


Fig. A2 - Angles and distances in the plane of the fence

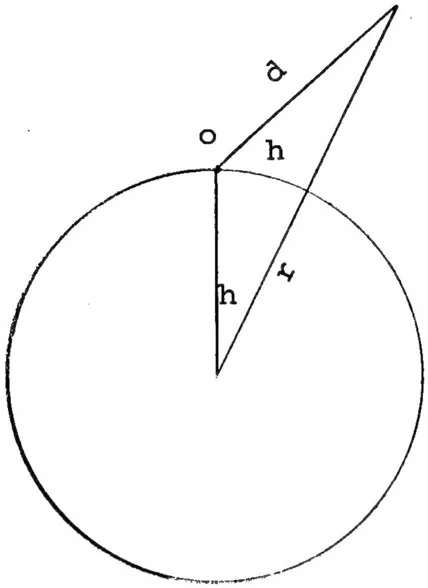


Fig. A3 - Geometrical relationship between the subsatellite point and an observer on the WS-434 Great Circle

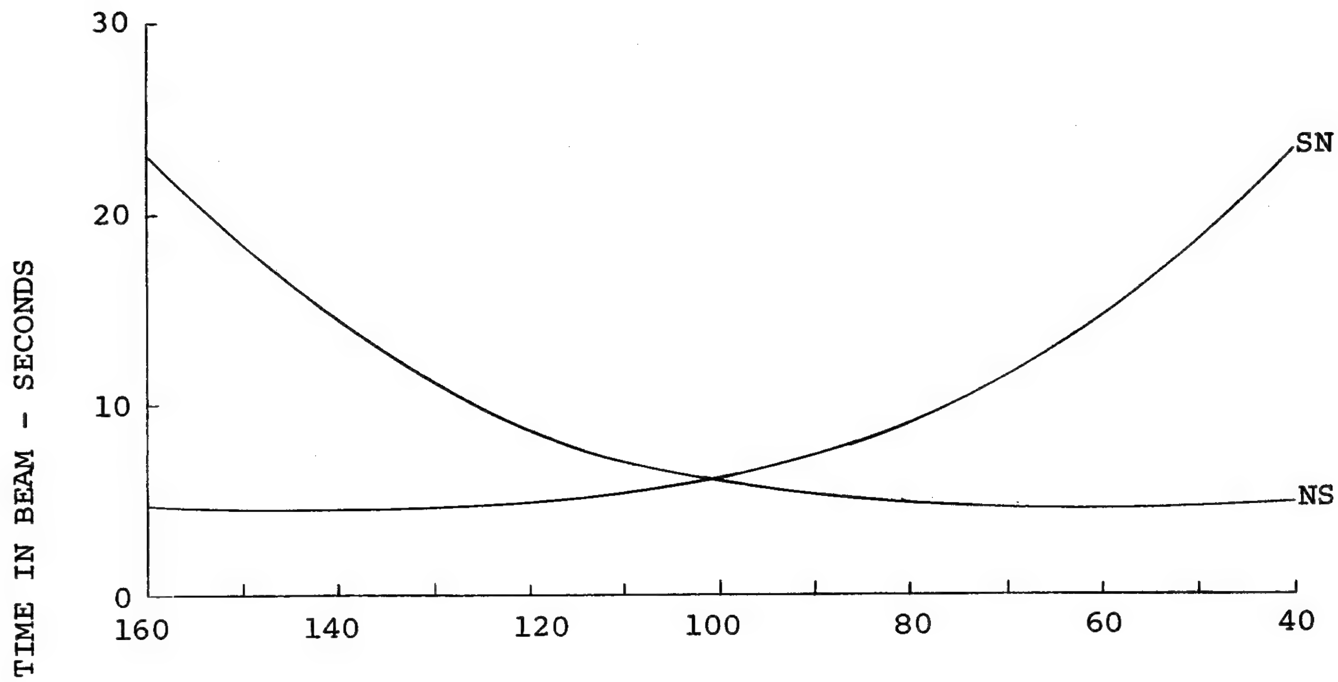
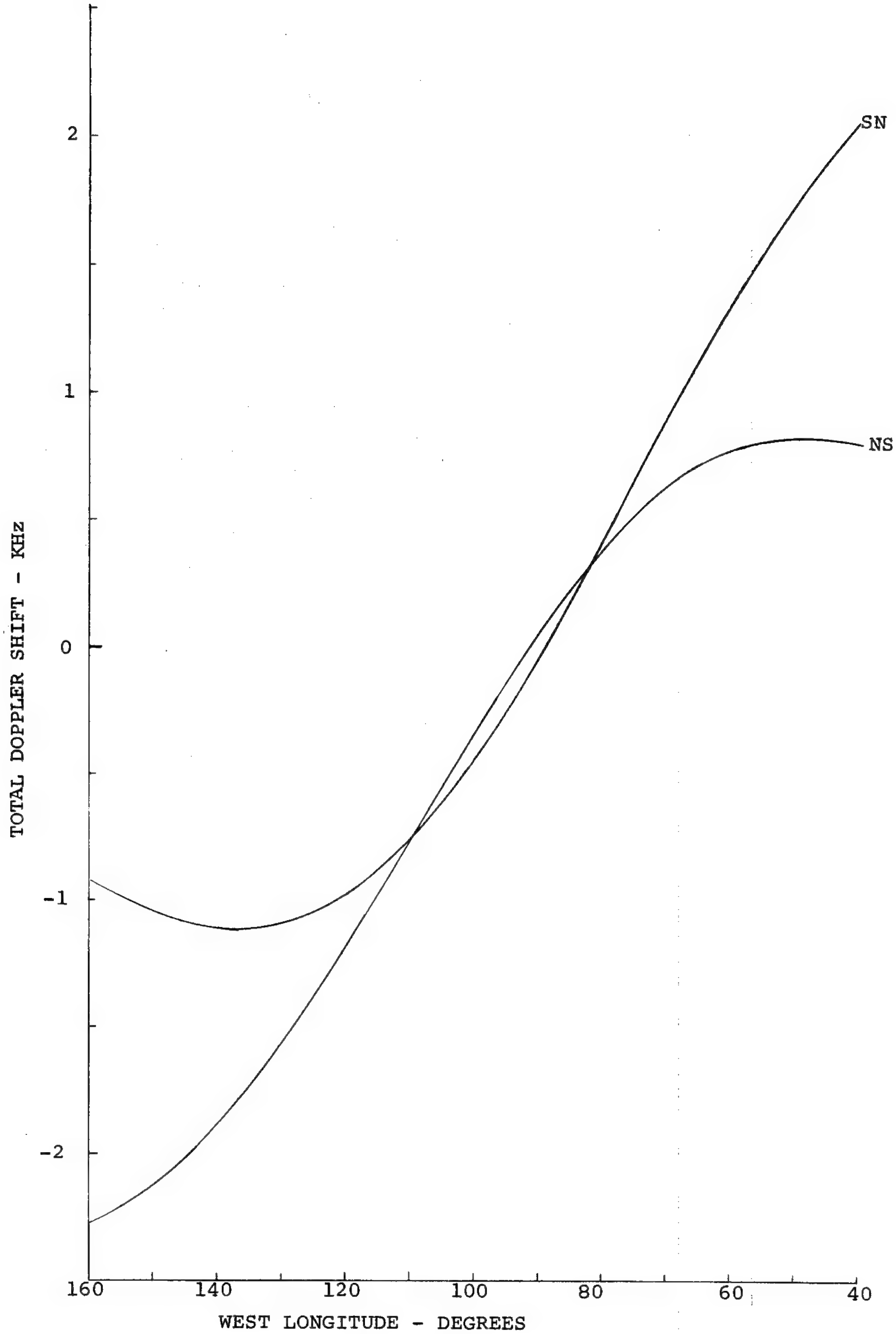


Fig. A4 - Time-in beam vs longitude for Timation III



(U) Fig. A5 - Total doppler shift vs longitude for Timation III at Ft. Stewart

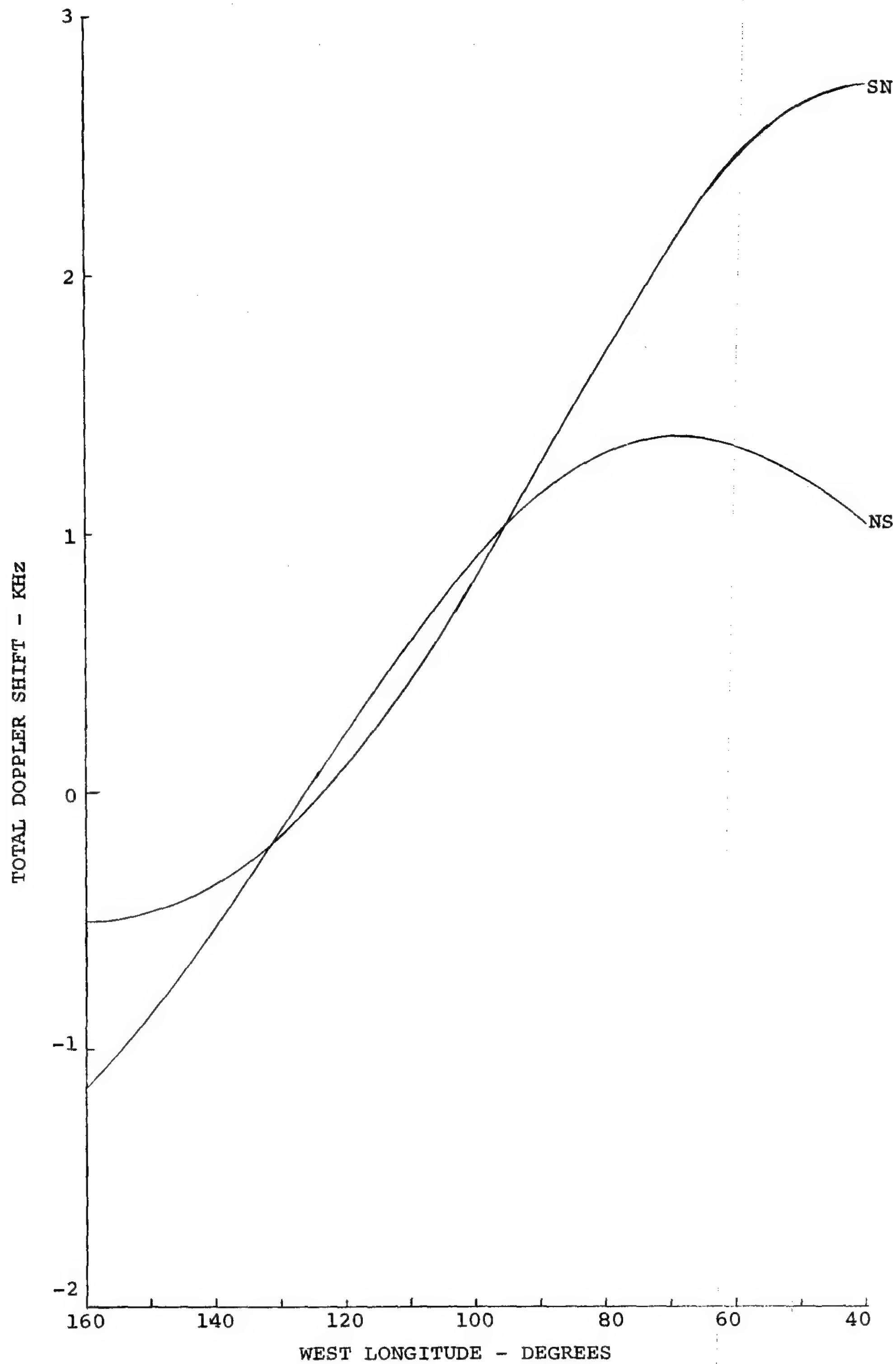
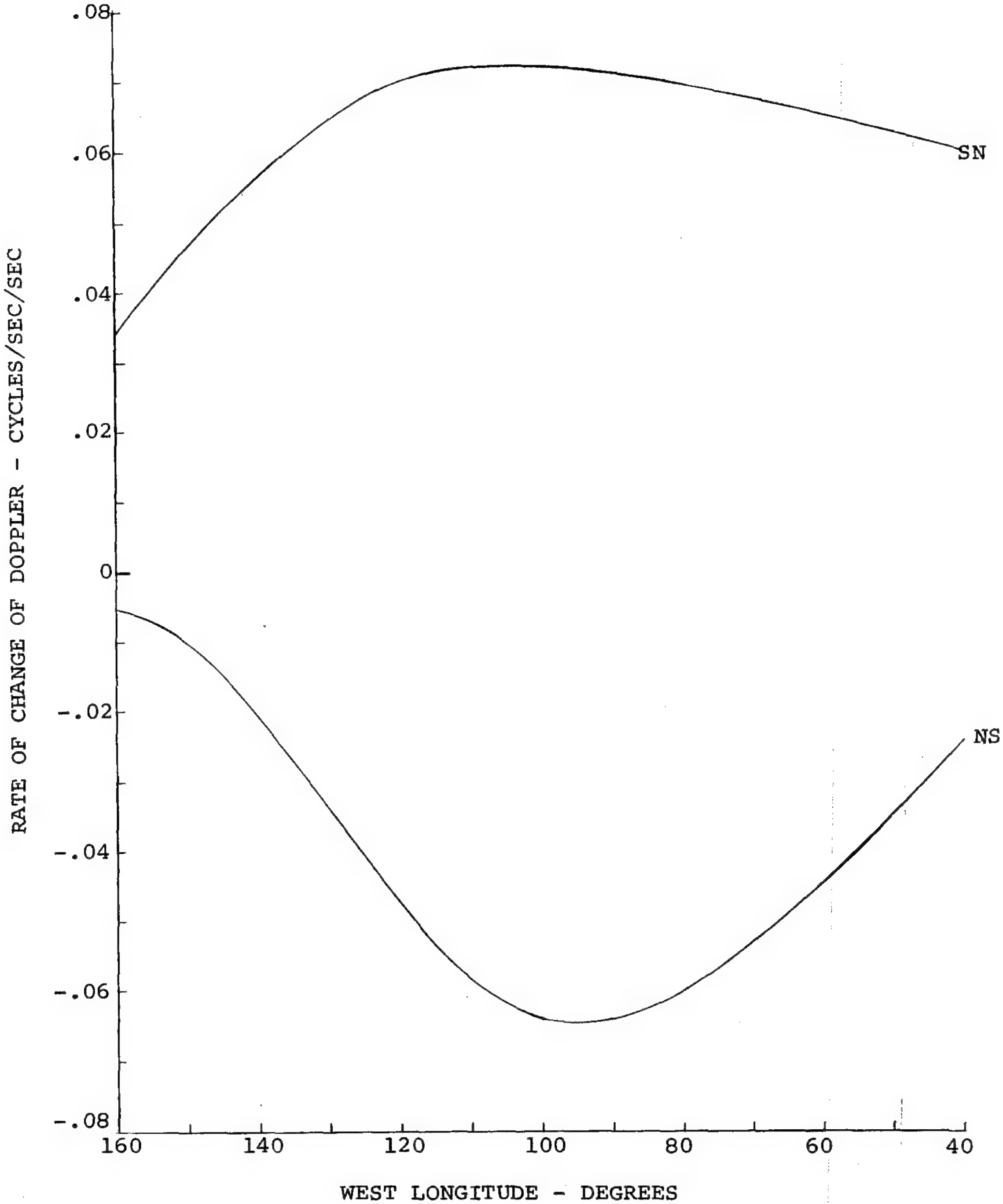


Fig. A6 - Total doppler shift vs longitude for Timation III at Maui



(U) Fig. A7 - Rate of change of doppler vs longitude for Timation III from Ft. Stewart

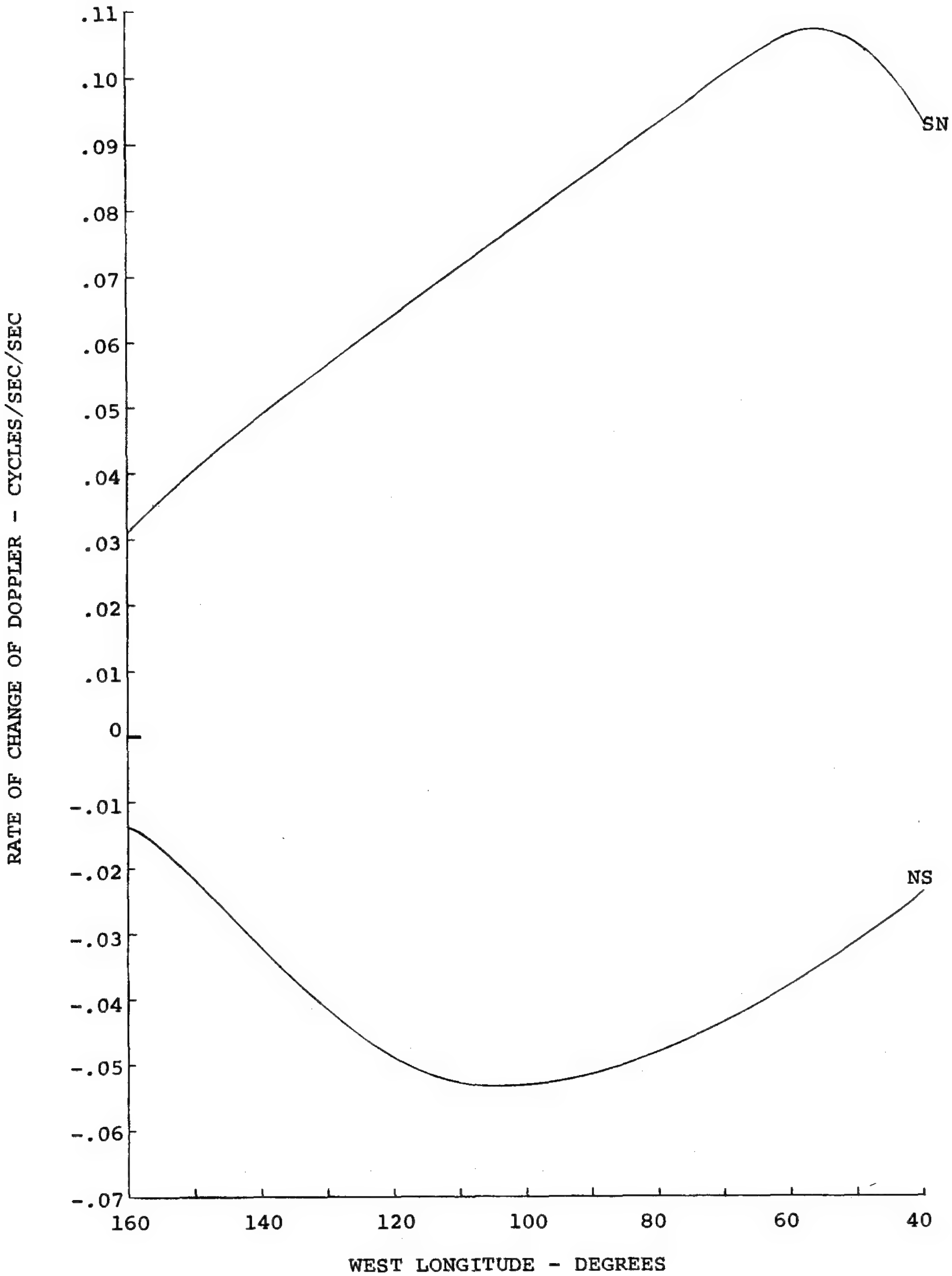


Fig. A8 - Rate of change of doppler vs longitude for Timation III from Maui

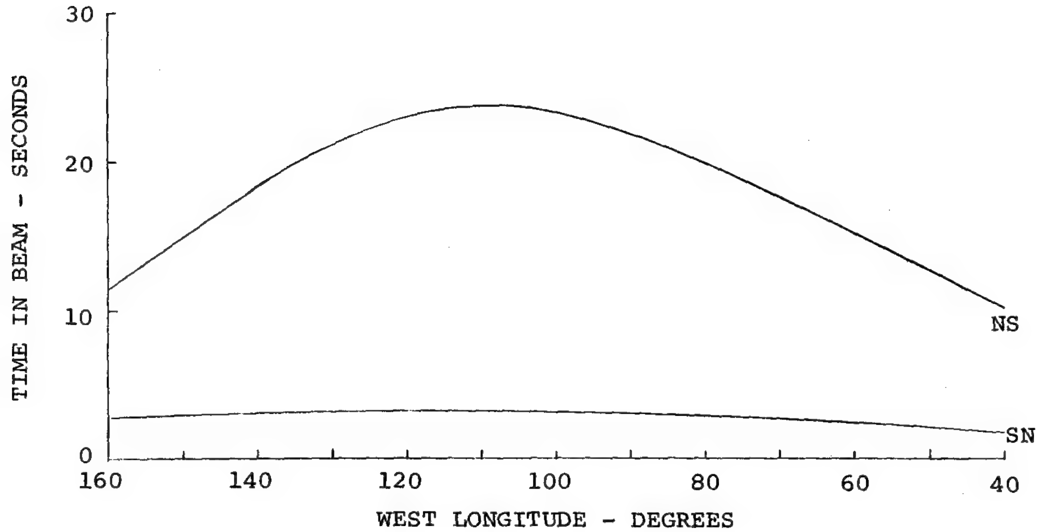


Fig. A9 - Time in beam vs longitude for Molniya

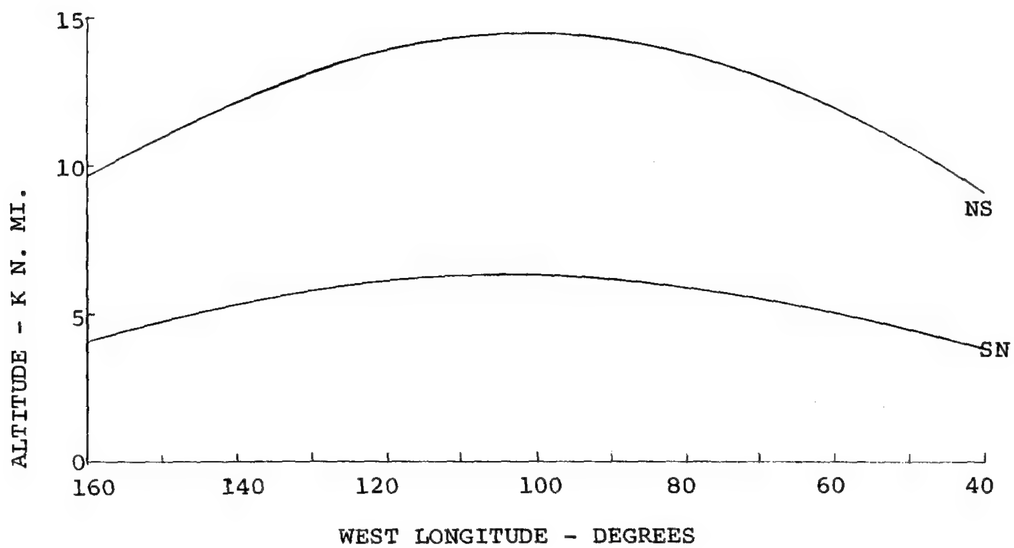
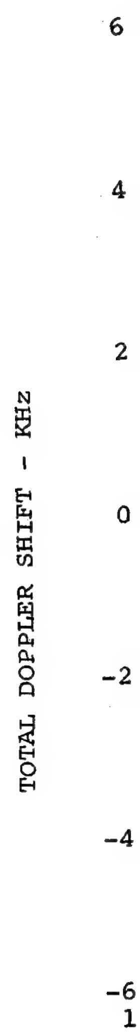


Fig. A10 - Altitude vs longitude for Molniya



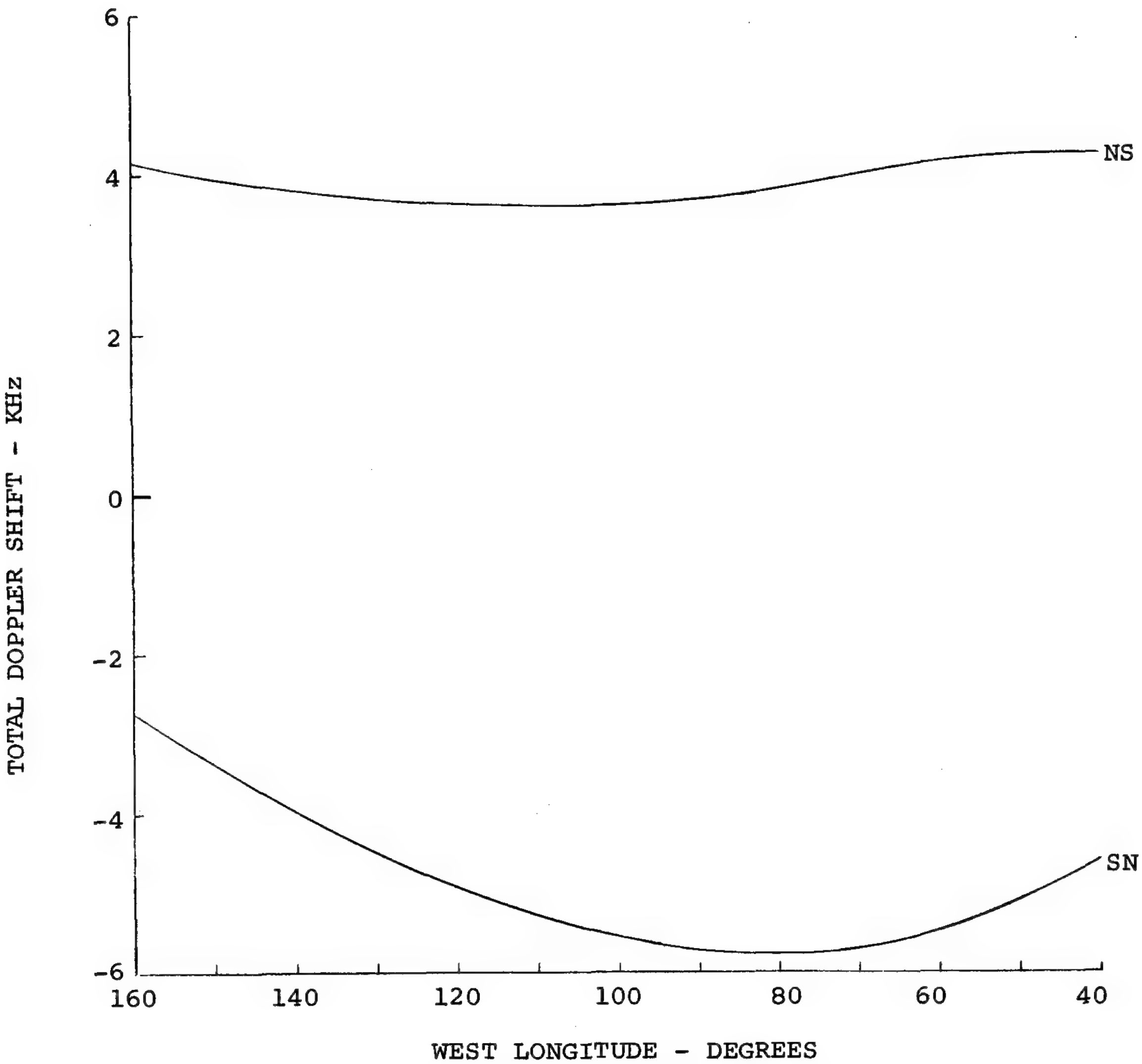


Fig. A11 - Total doppler shift vs longitude for Molniya at Ft. Stewart

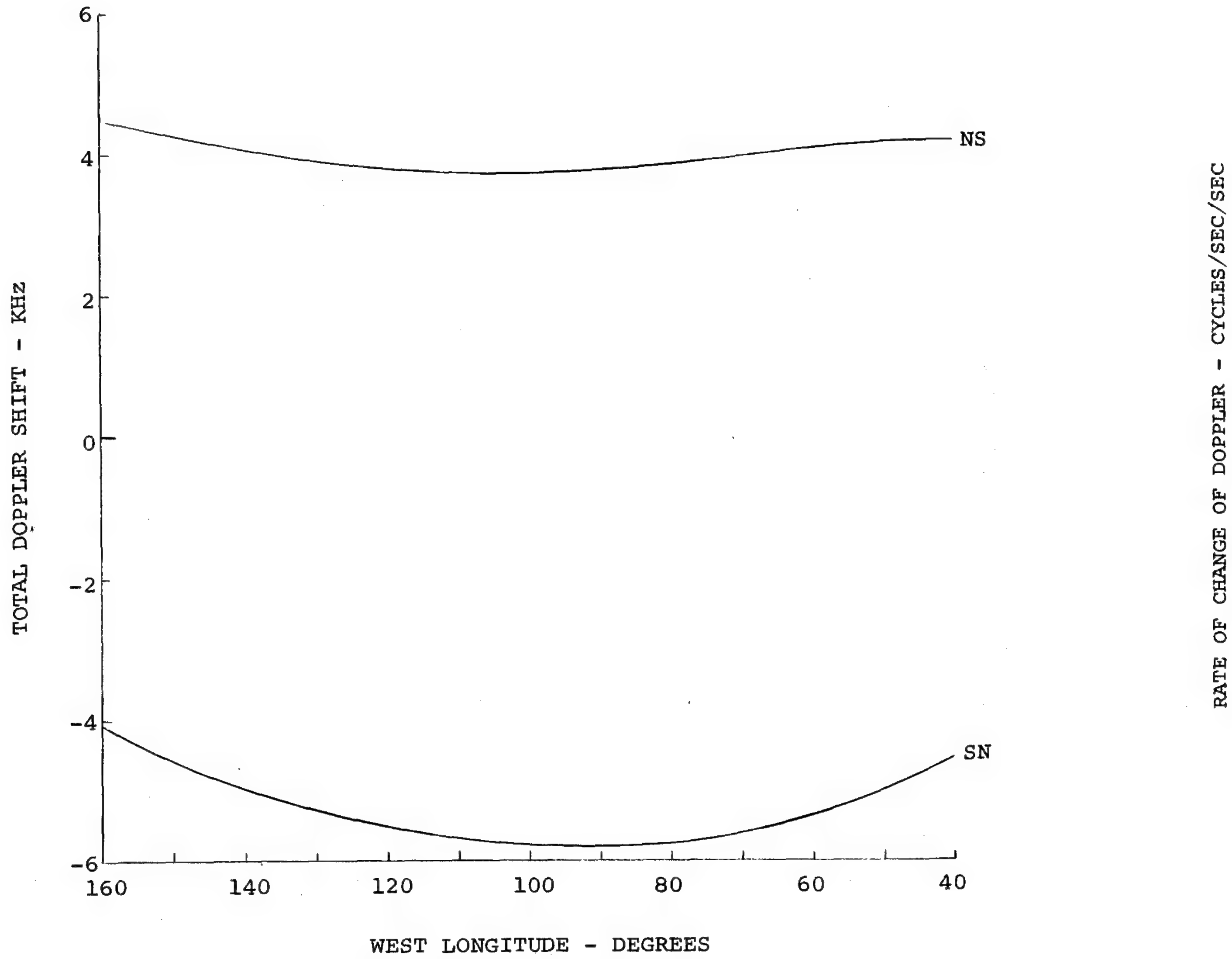


Fig. A12 - Total doppler shift vs longitude for Molniya at Maui

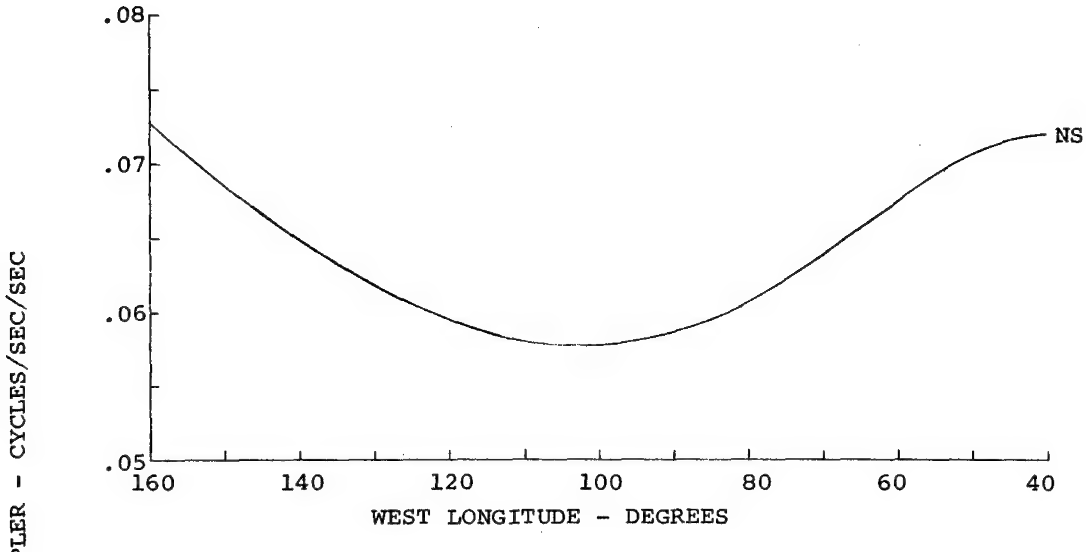


Fig. A13 - Rate of change of doppler vs longitude for Molniya from Maui (NS passes)

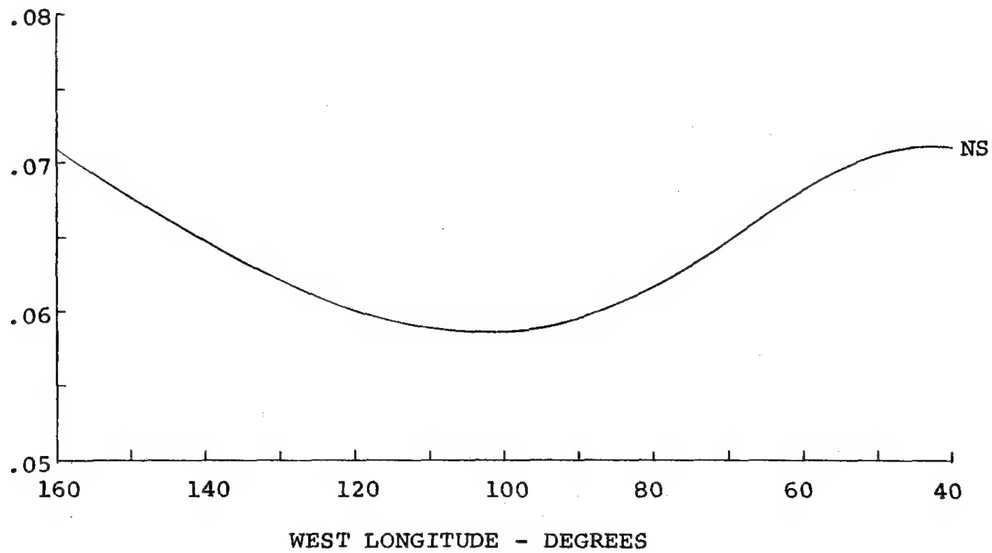


Fig. A14 - Rate of change of doppler vs longitude for Molniya from Ft. Stewart (NS passes)

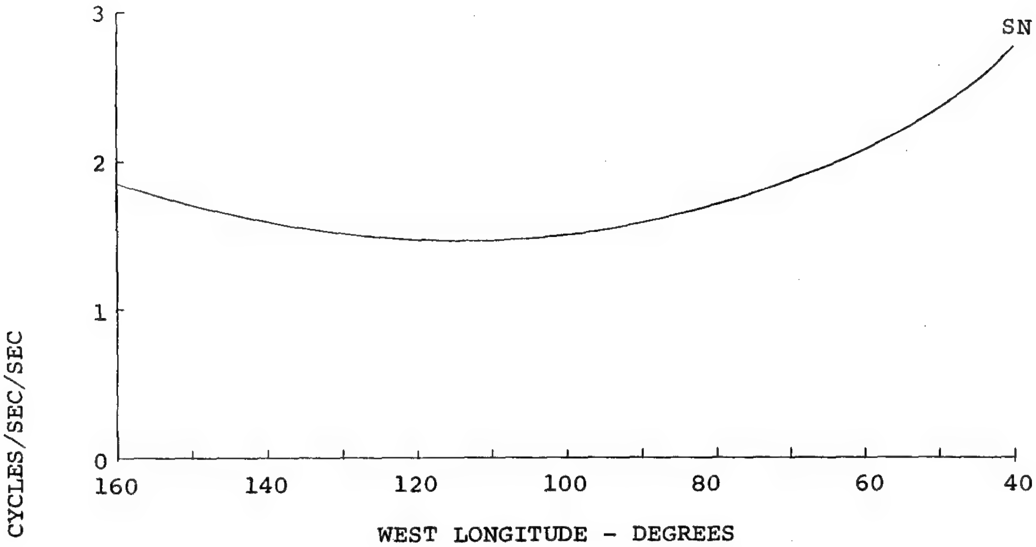


Fig. A15 - Rate of change of doppler vs longitude for Molniya from Ft. Stewart (SN passes)

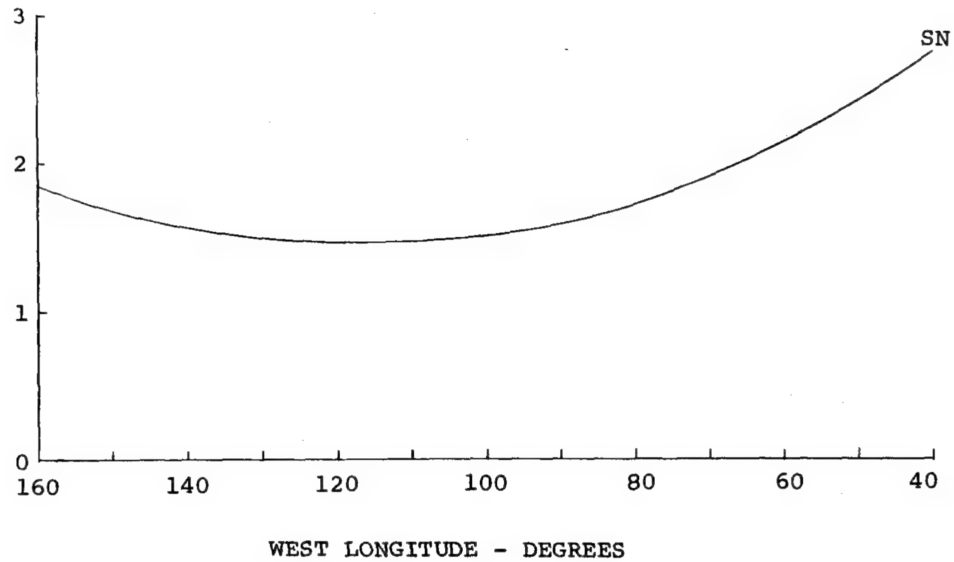


Fig. A16 - Rate of change of doppler vs longitude for Molniya from Maui (SN passes)

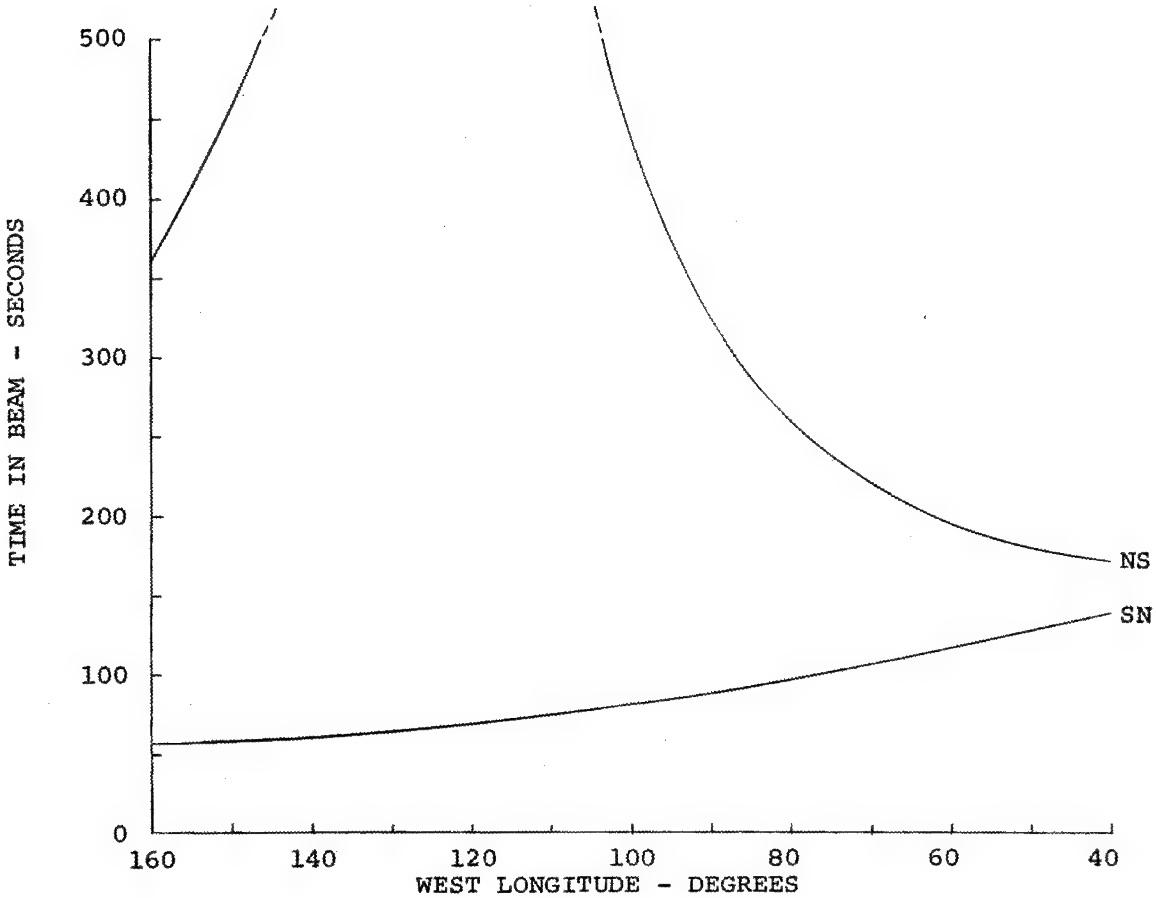


Fig. A17 - Time-in beam vs longitude for OGOI

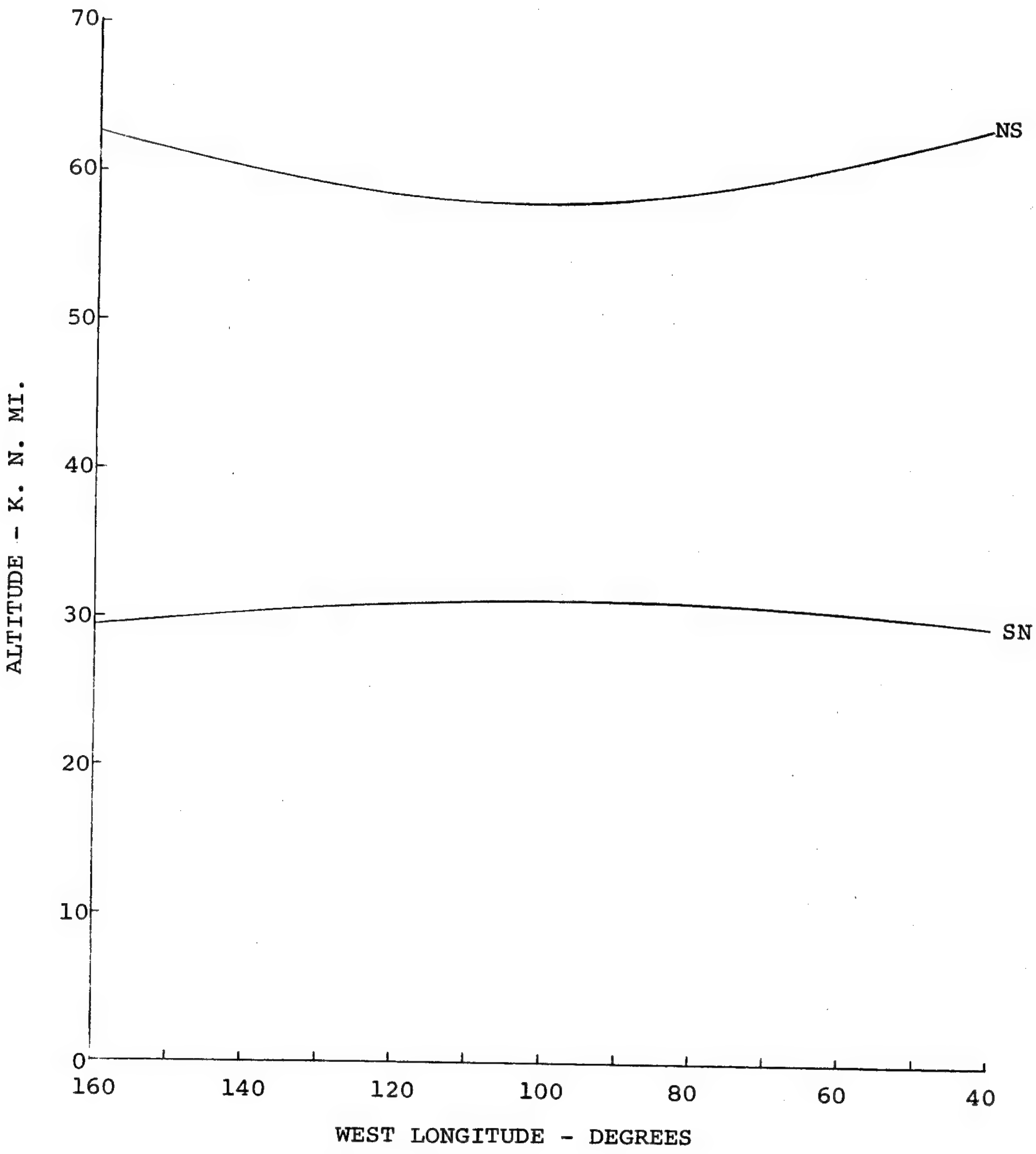


Fig. A18 - Altitude vs longitude for OGOI

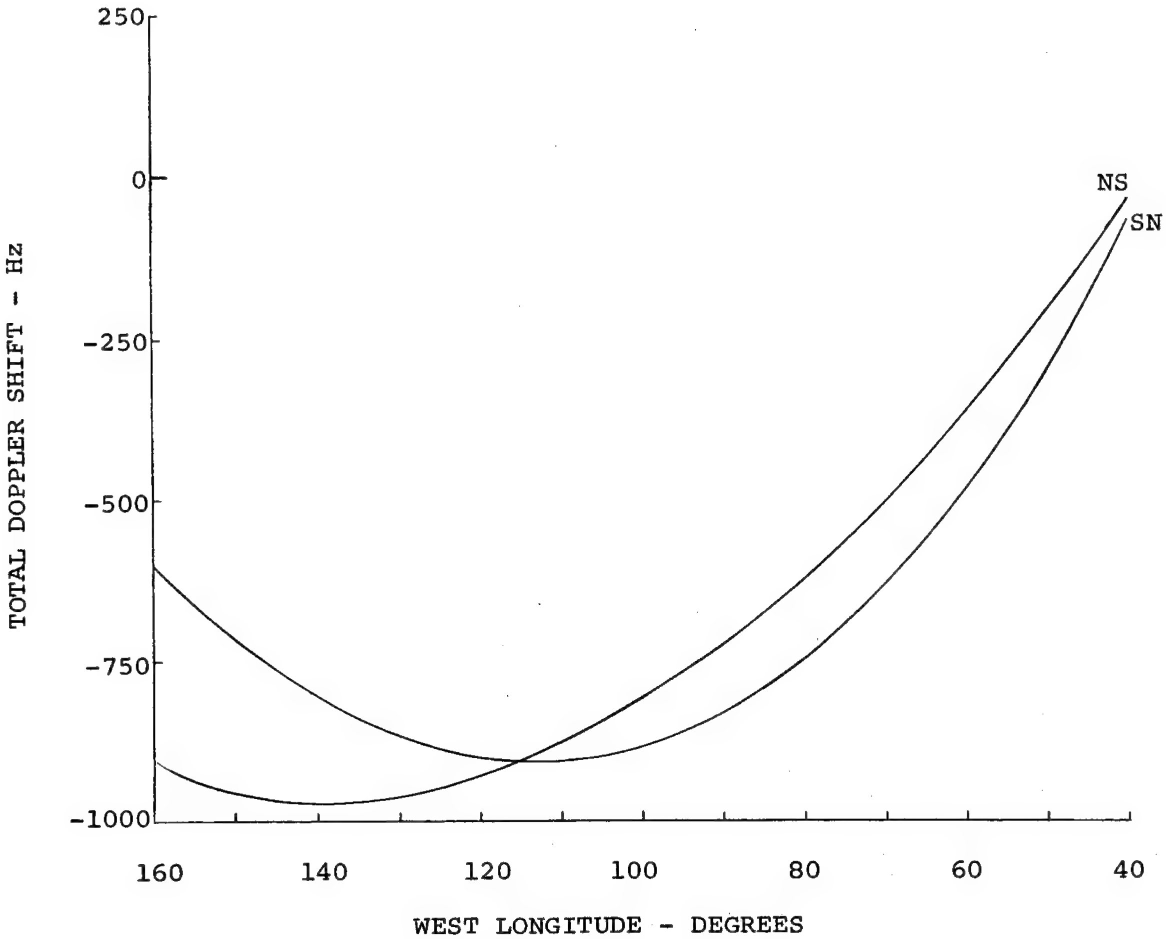


Fig. A19 - Total doppler shift vs longitude for OGOI at Ft. Stewart

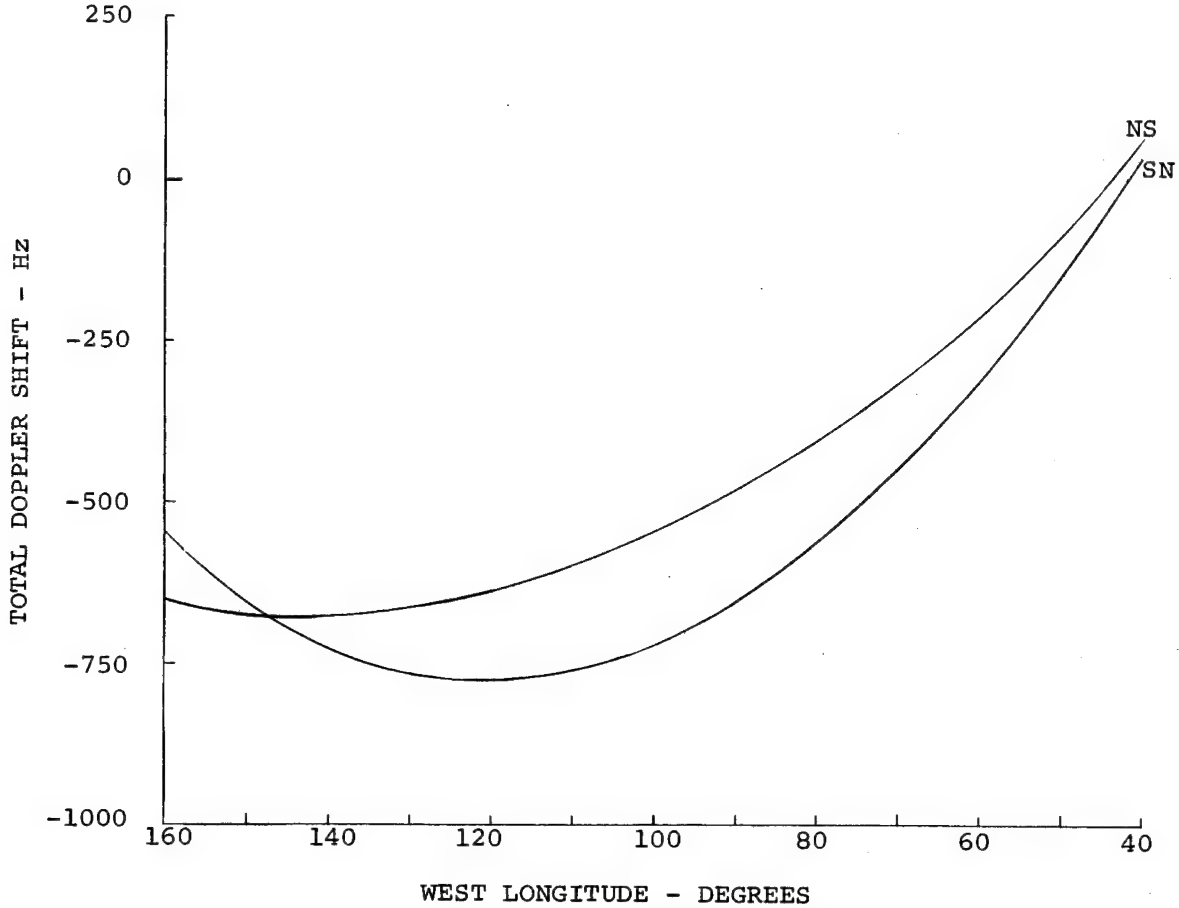


Fig. A20 - Total doppler shift vs longitude for OGOI at MAUI

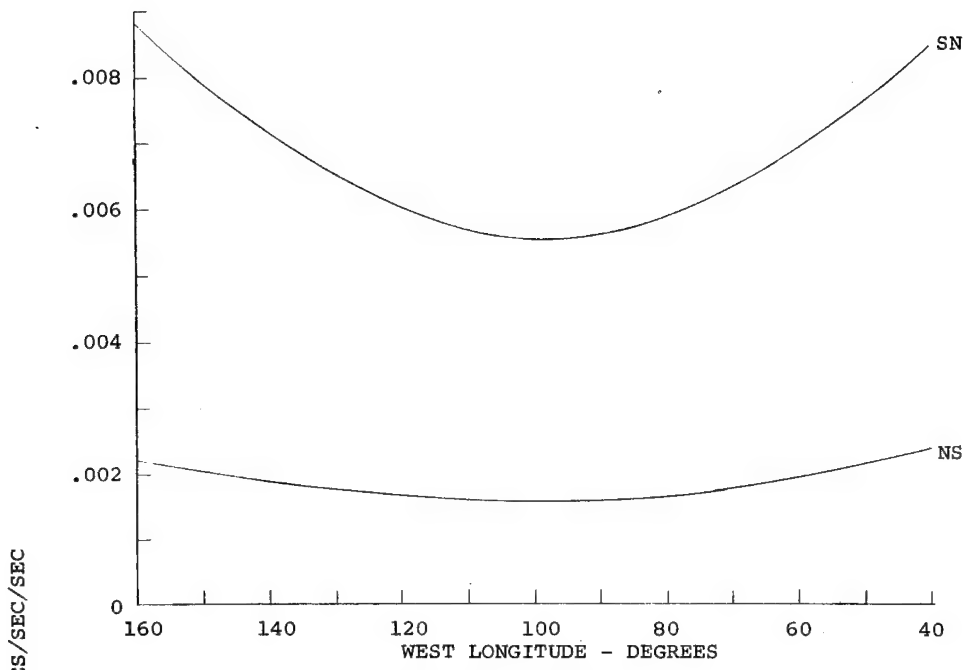


Fig. A21 - Rate of change of doppler vs longitude for OGOI from Maui

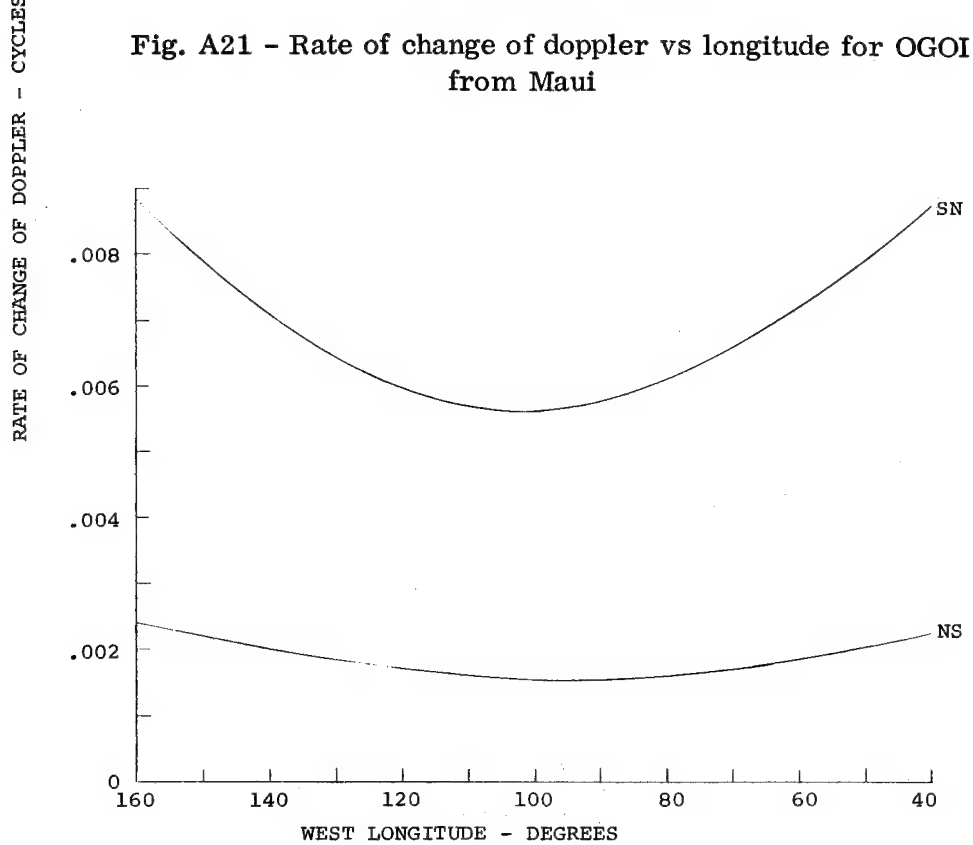
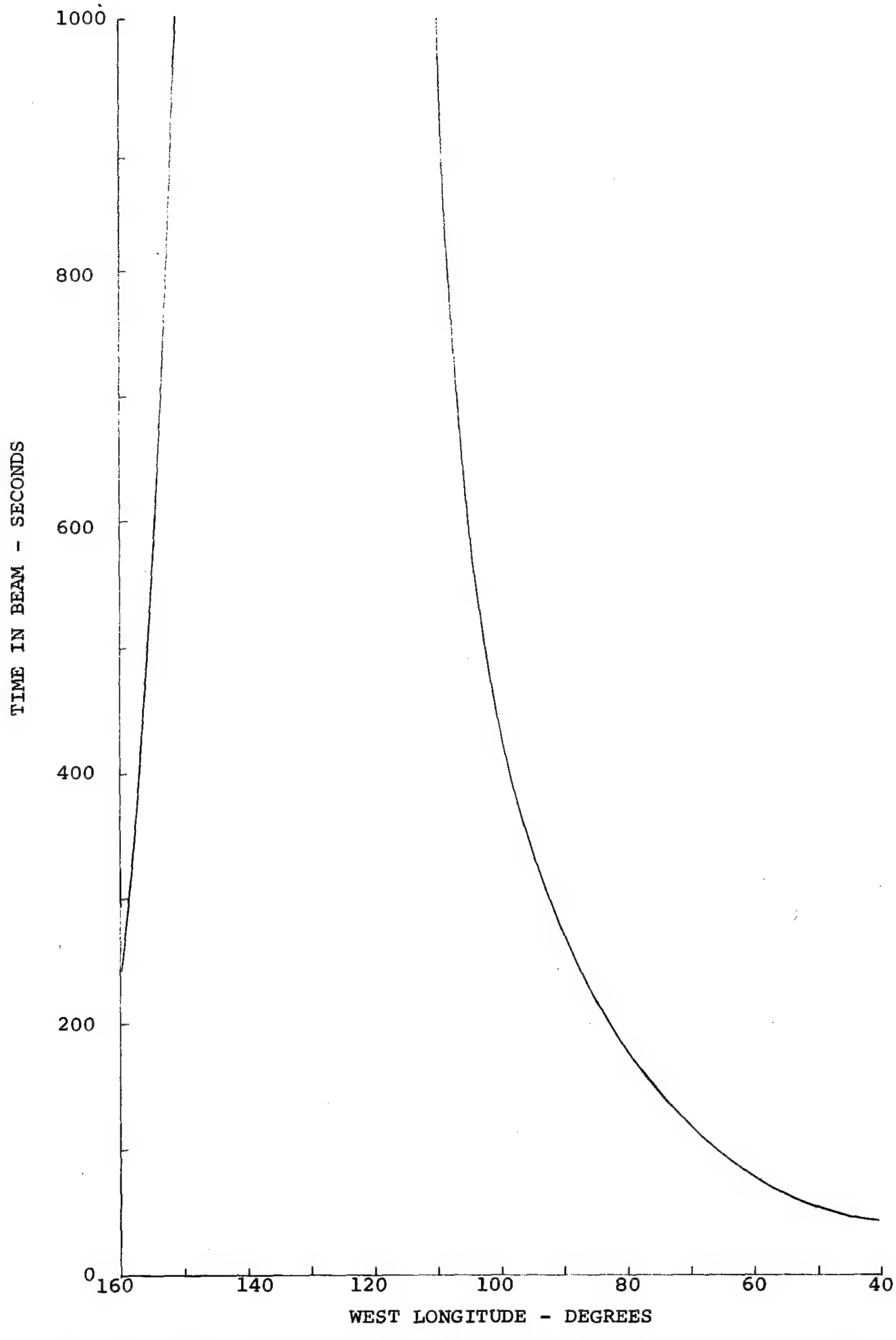
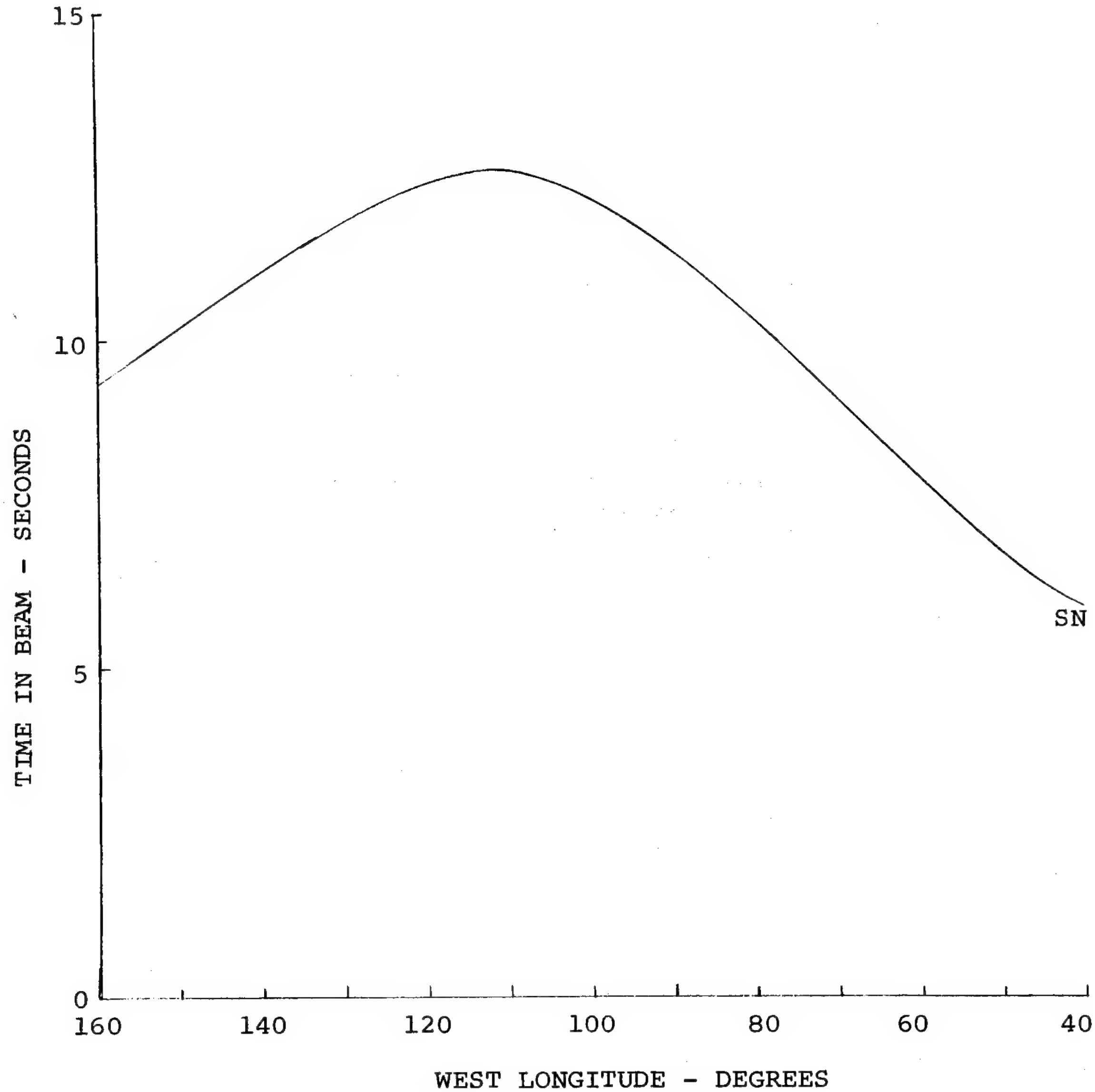


Fig. A22 - Rate of change of doppler vs longitude for OGOI from Ft. Stewart



(U) Fig. A23 - Time in beam vs longitude for Prognoz N-S Pass



(U) Fig. A24 - Time in beam vs longitude for Prognoz S-N Pass

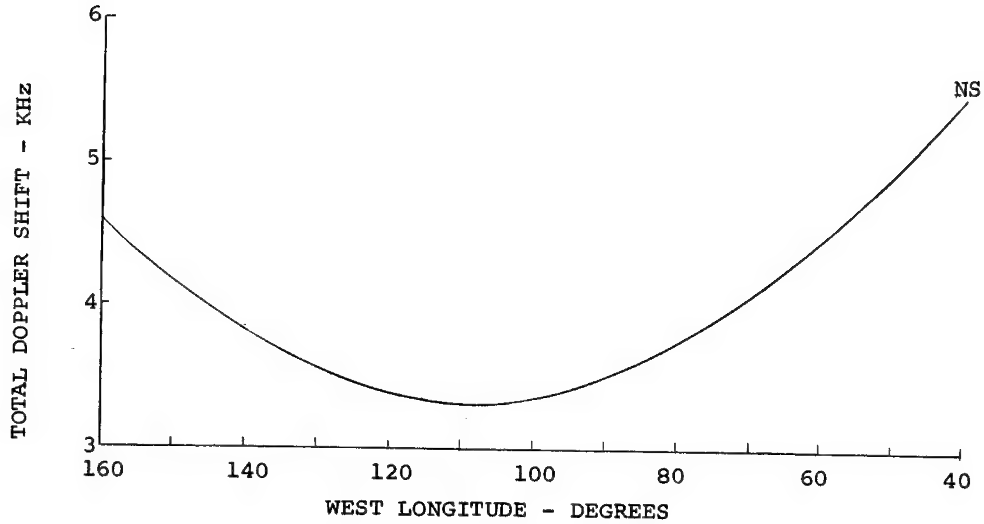


Fig. A25 - Total doppler shift vs longitude for Prognoz
at Ft. Stewart

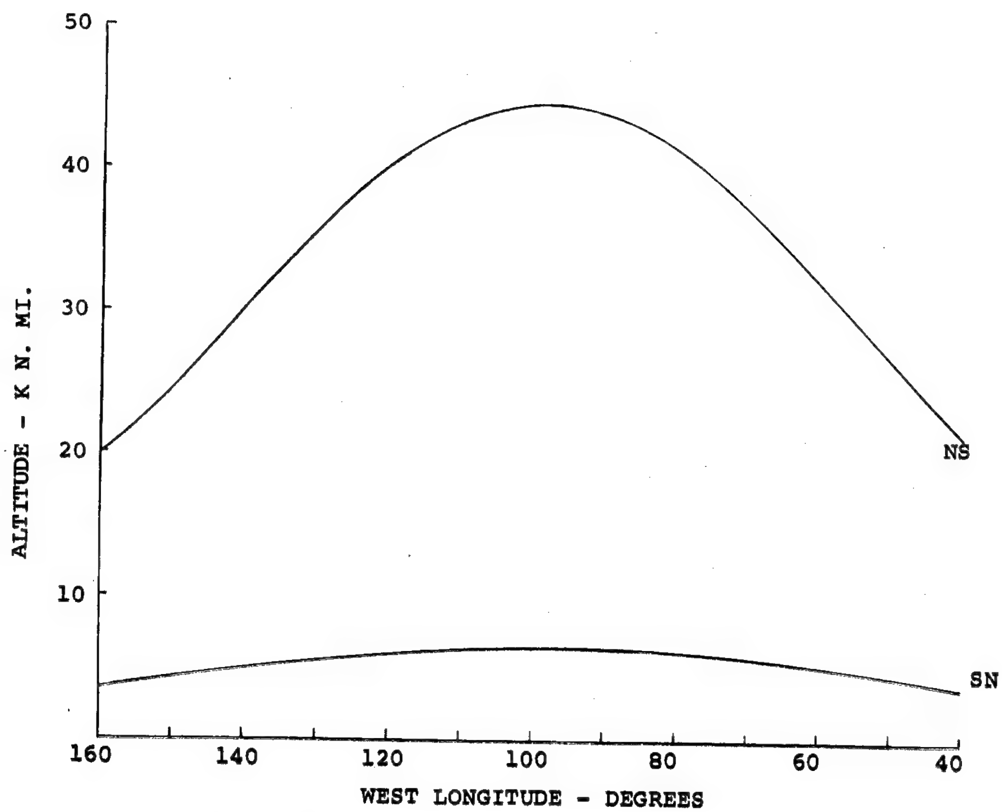


Fig. A26 - Altitude vs longitude for Prognoz

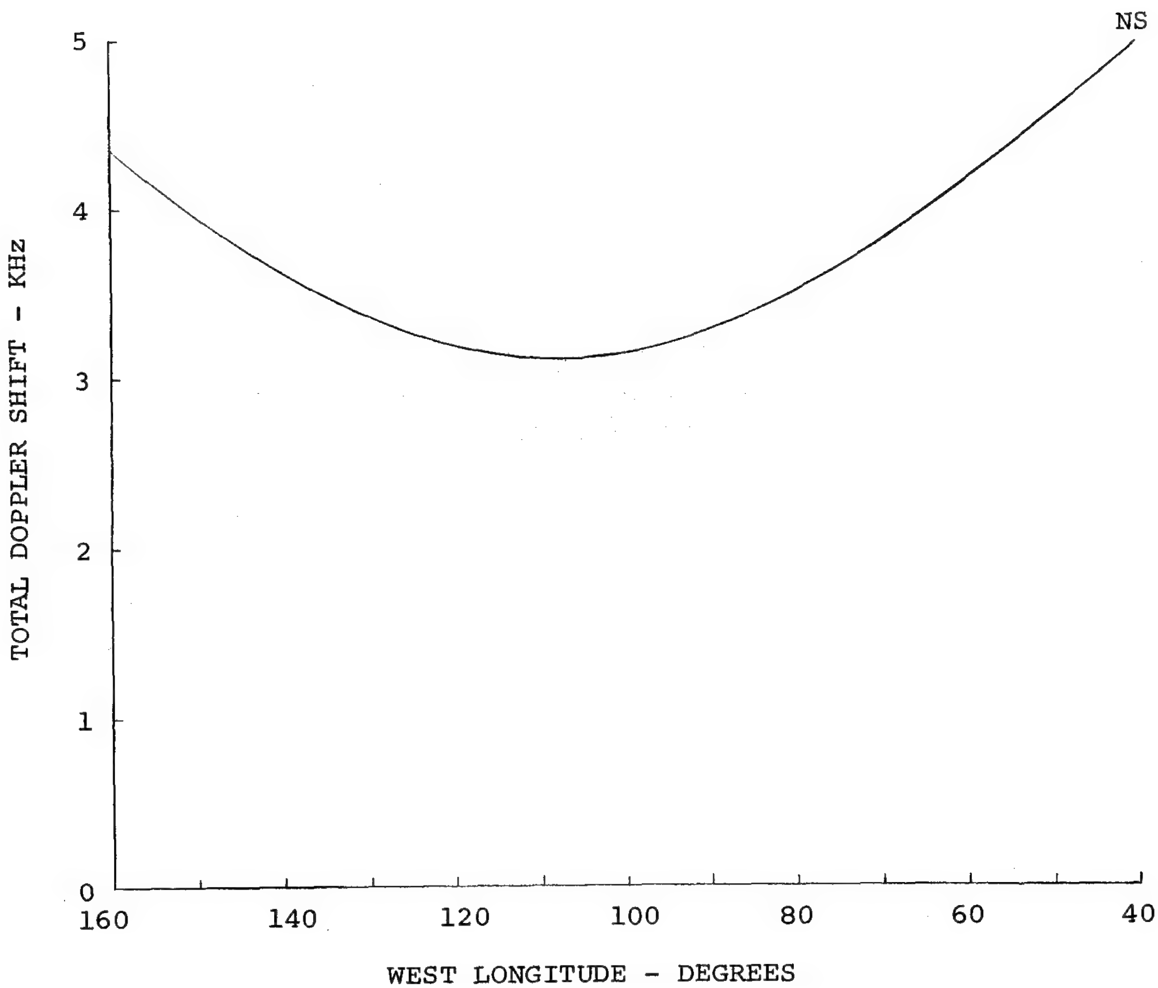


Fig. A27 - Total doppler shift vs longitude for Prognoz at Maui

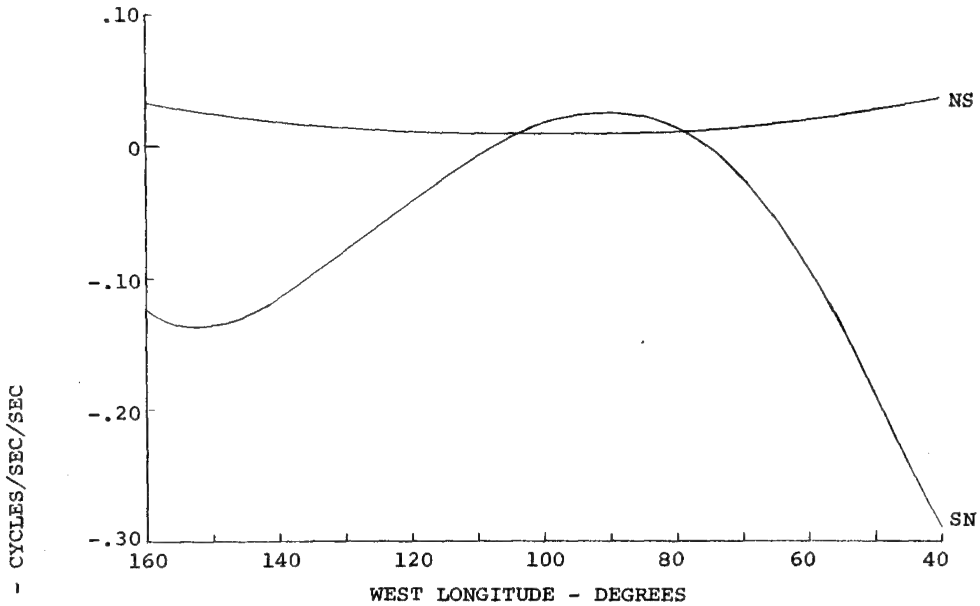


Fig. A28 - Rate of change of doppler vs longitude for Prognoz at Ft. Stewart

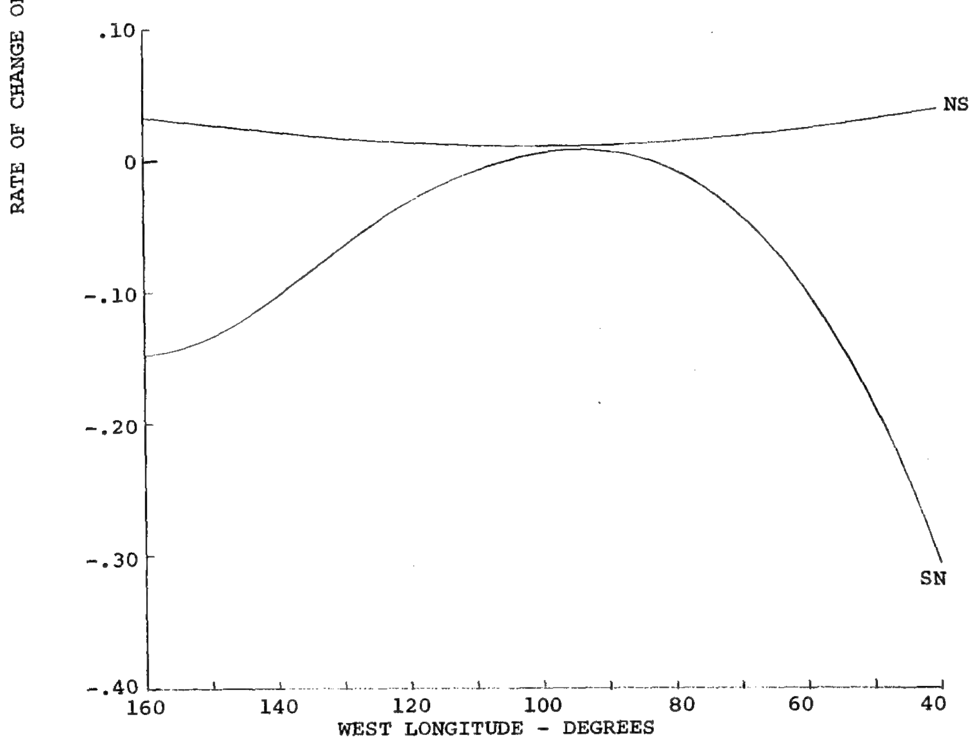


Fig. A29 - Rate of change of doppler vs longitude for Prognoz at Maui

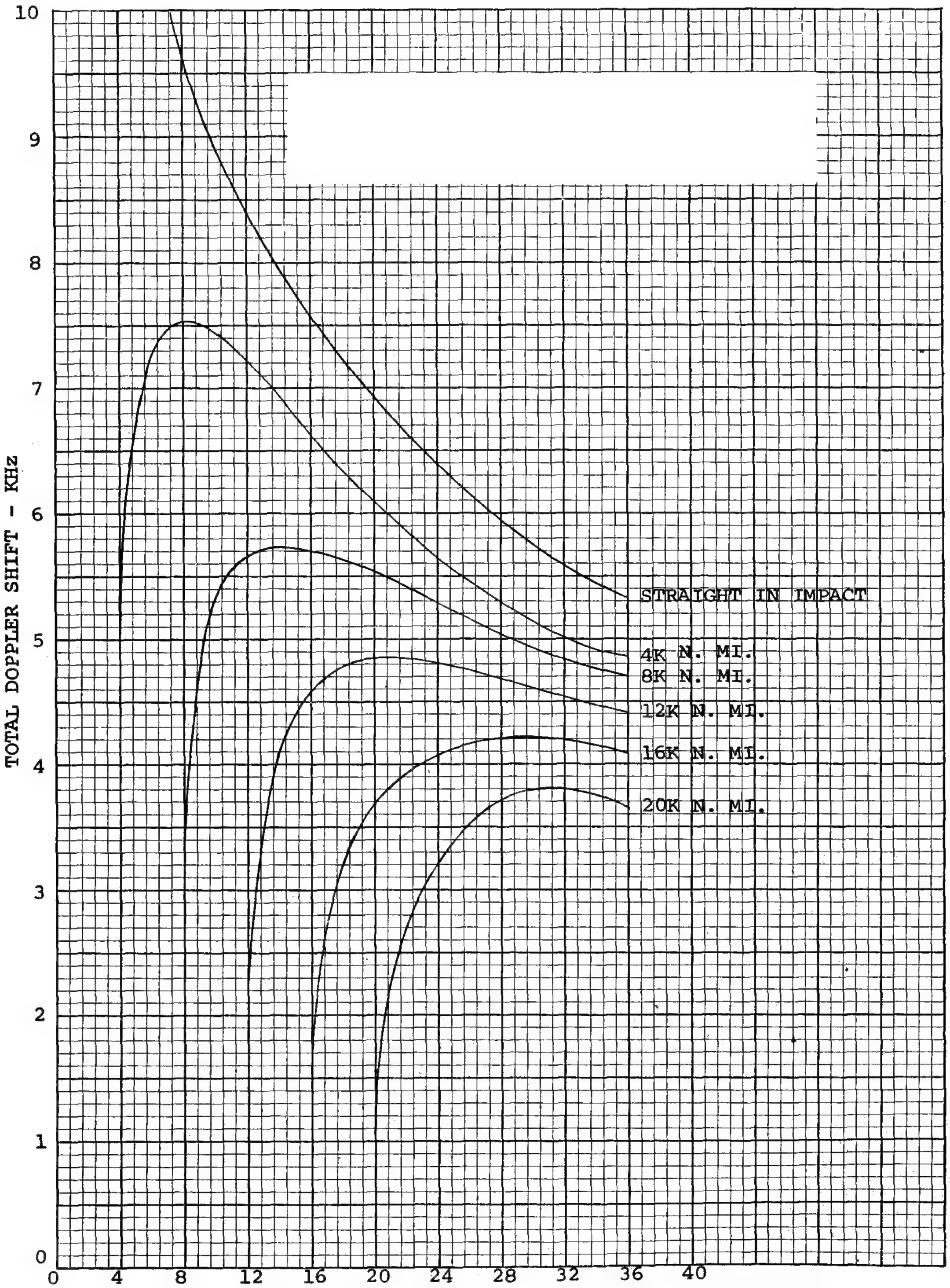


Fig. A30 - Total doppler shift vs altitude for various perigee heights in miles

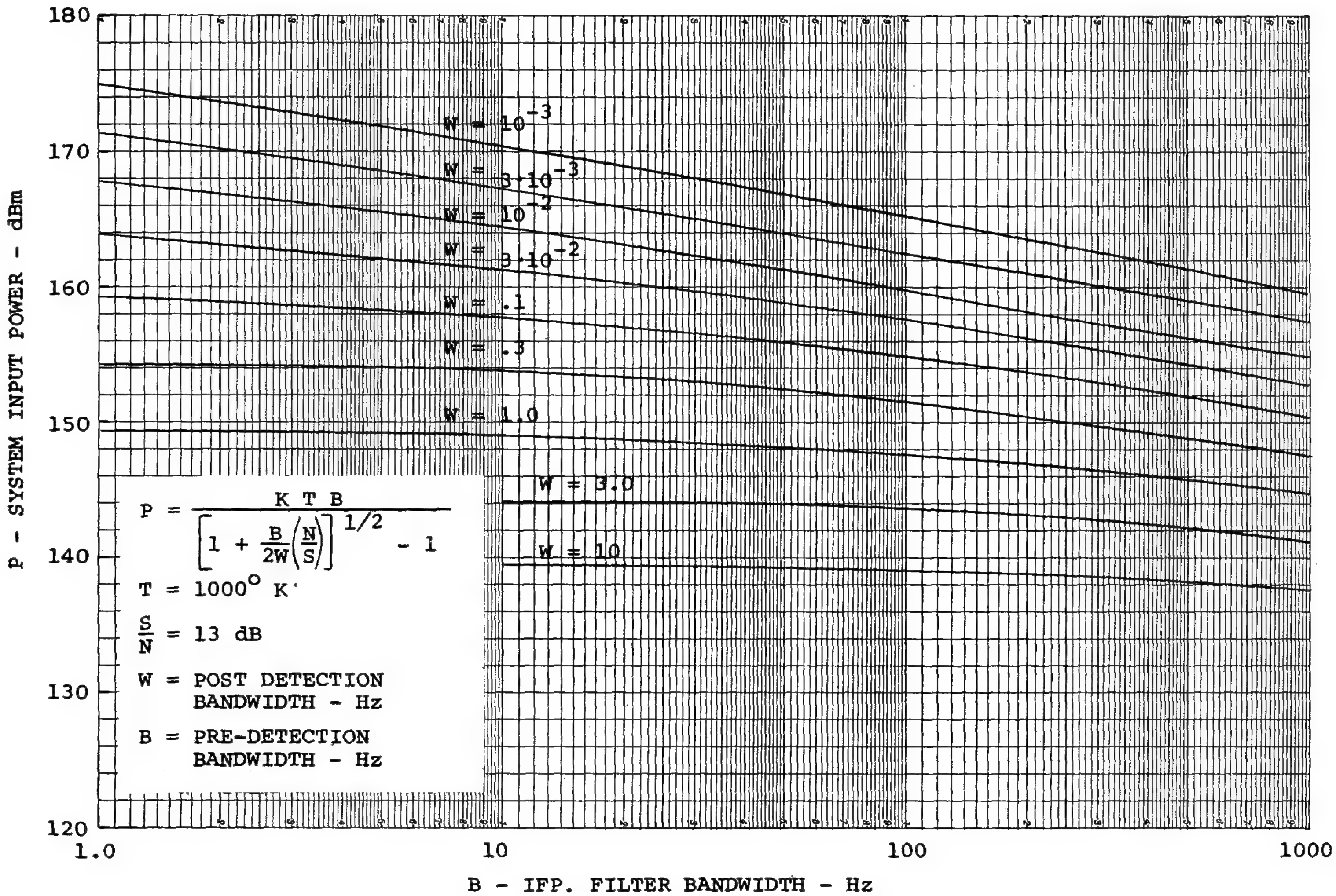
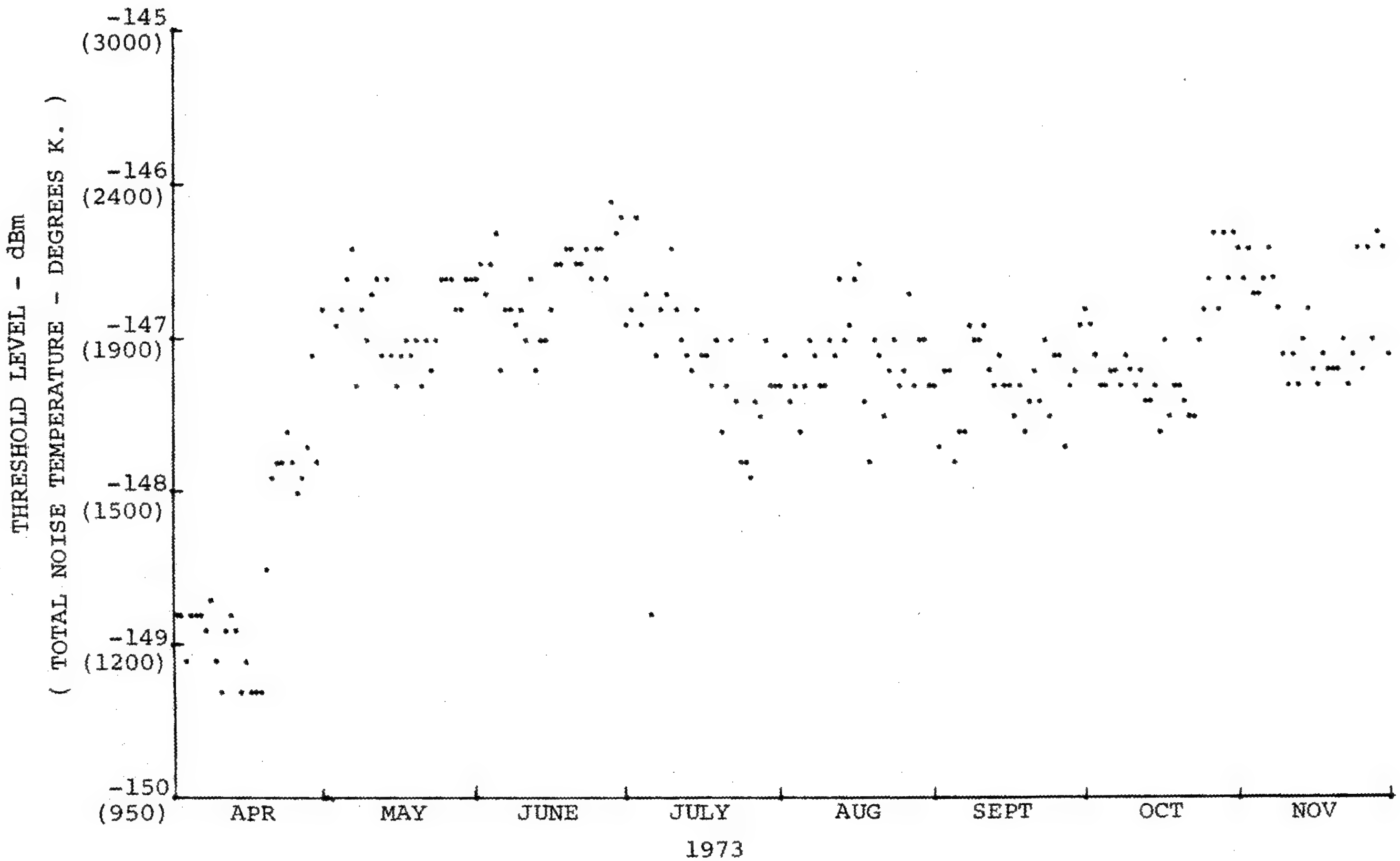


Fig. A31 - Detection system sensitivity



(U) Fig. A32 - Observed WS-434 detection threshold

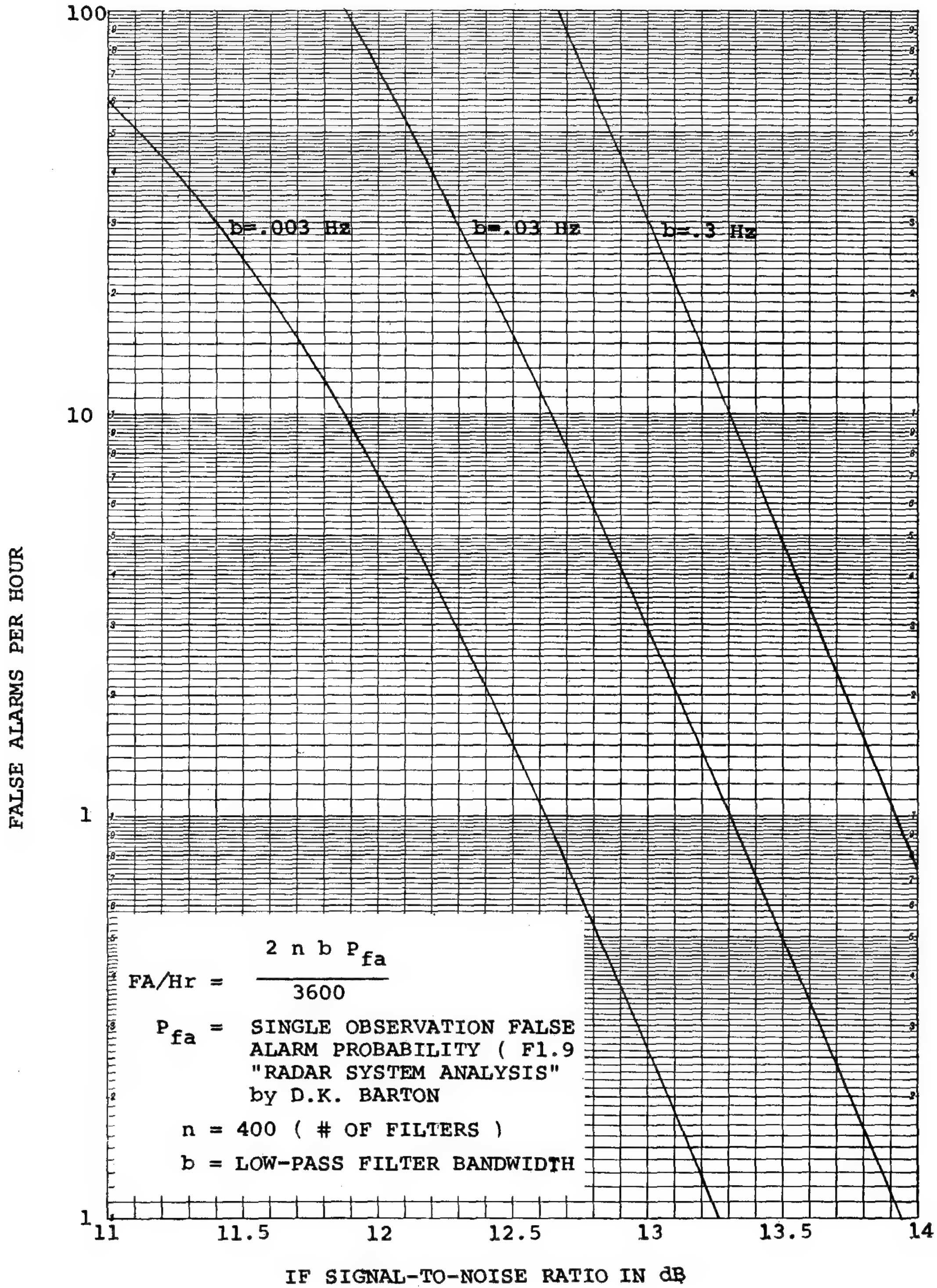
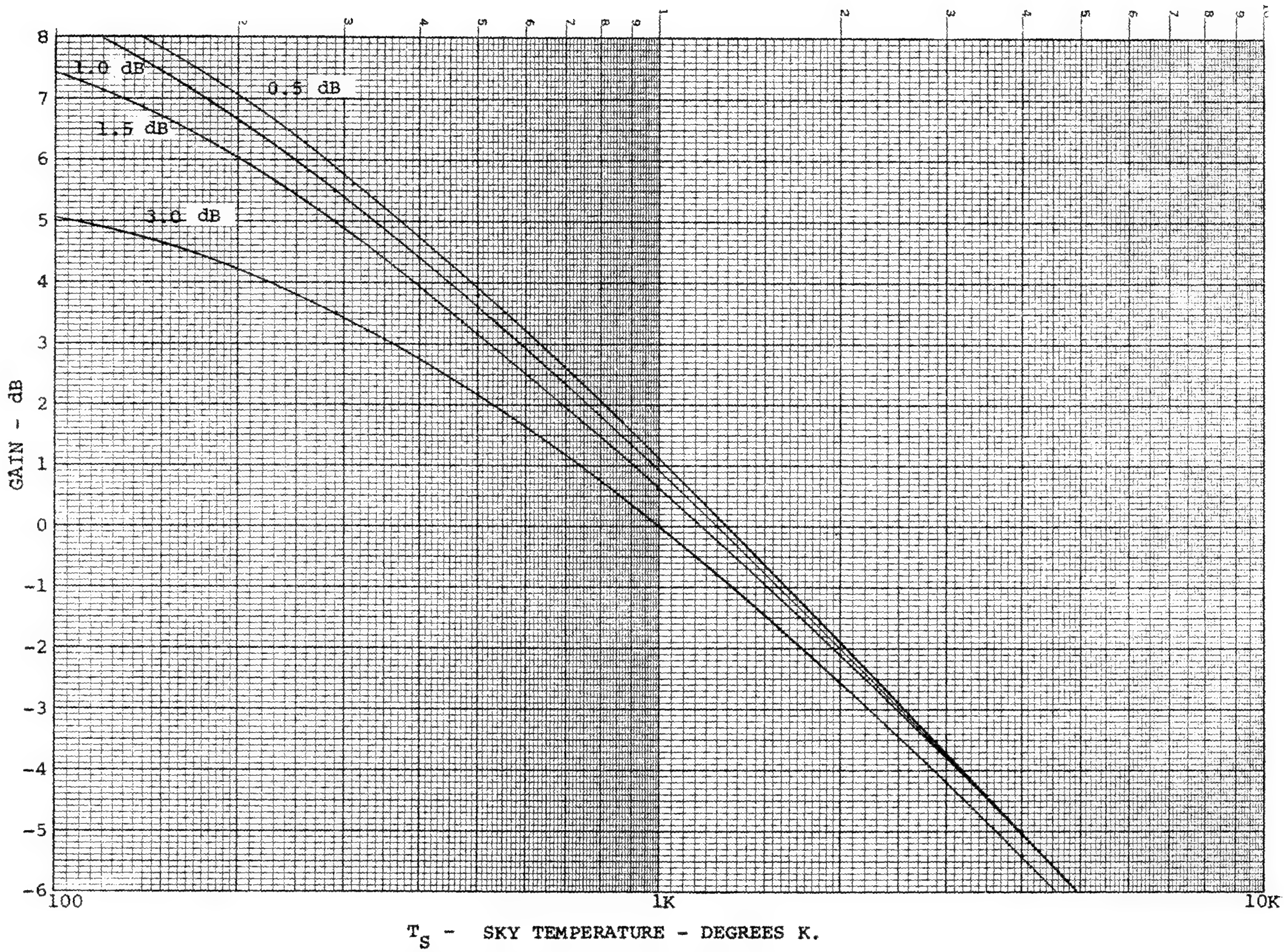


Fig. A33 - False alarm rate vs IF S/N ratio for 95% probability of detection



(U) Fig. A34 - Gain vs sky temperature for various receiving system noise figures referred to $T_S = 10^3$ °K, $N_F = 3$ dB

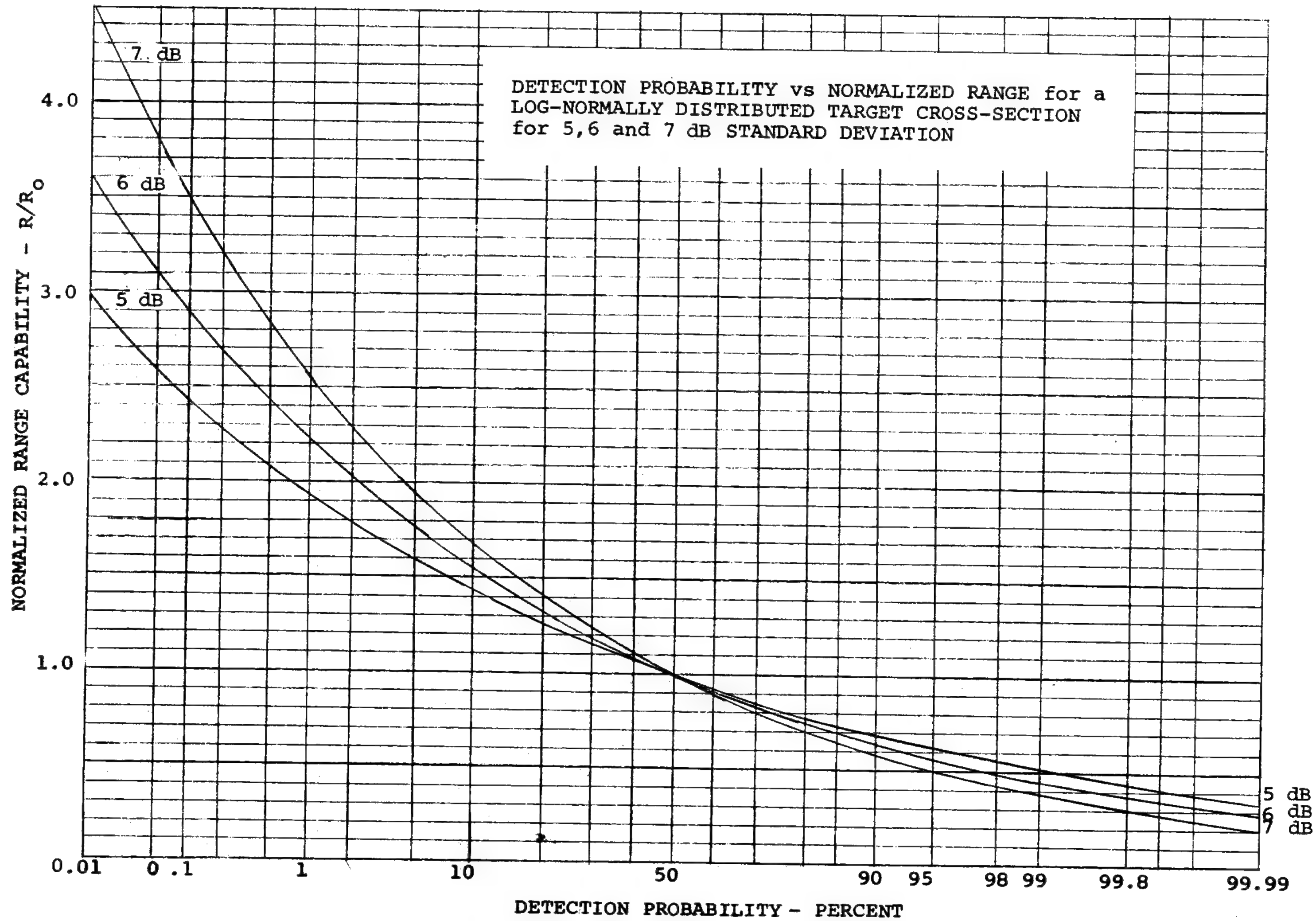


Fig. A35 - Detection probability vs normalized range for LOG-normal distributed target cross-section

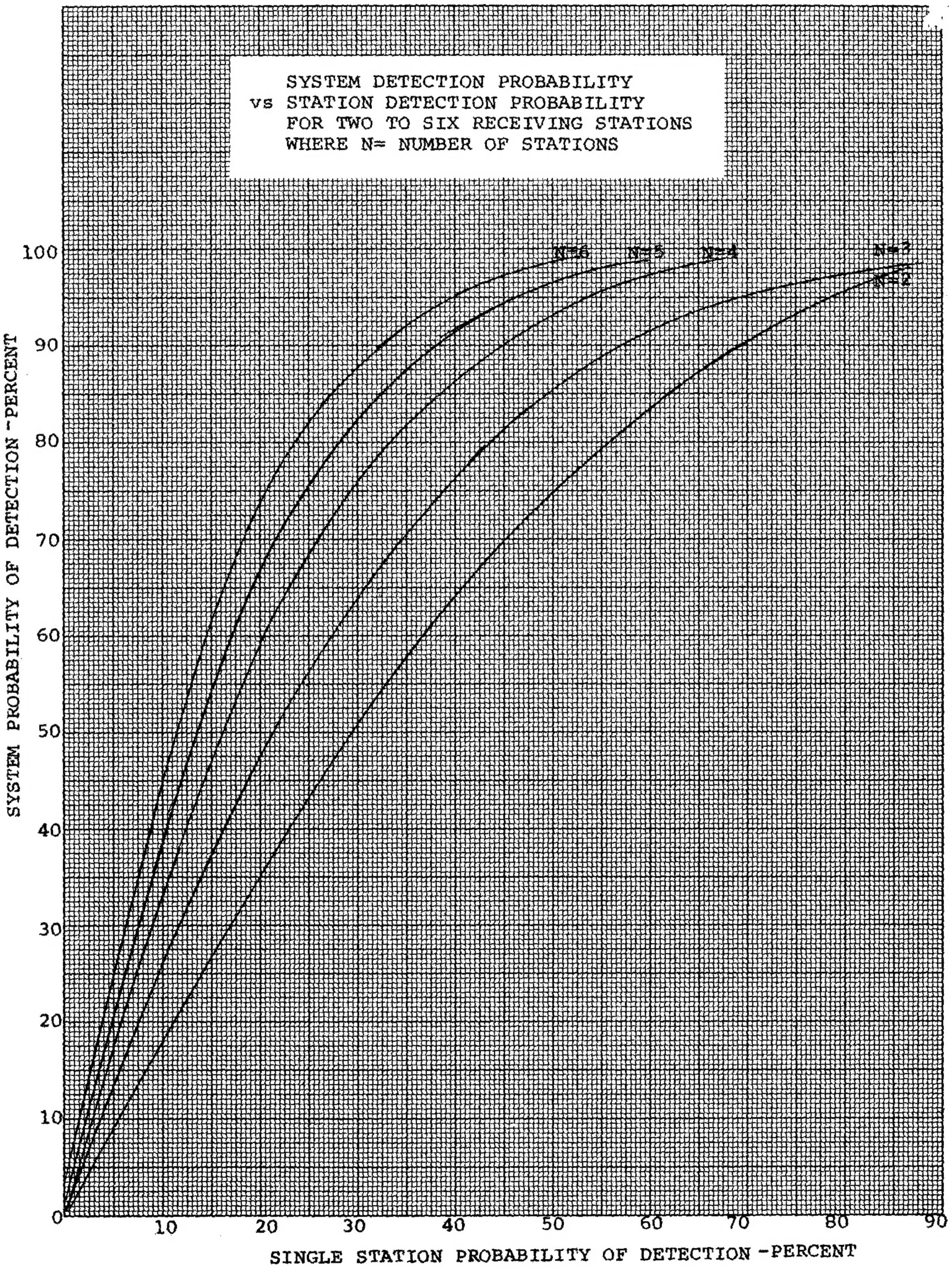


Fig. A36 - System detection probability vs station detection probability

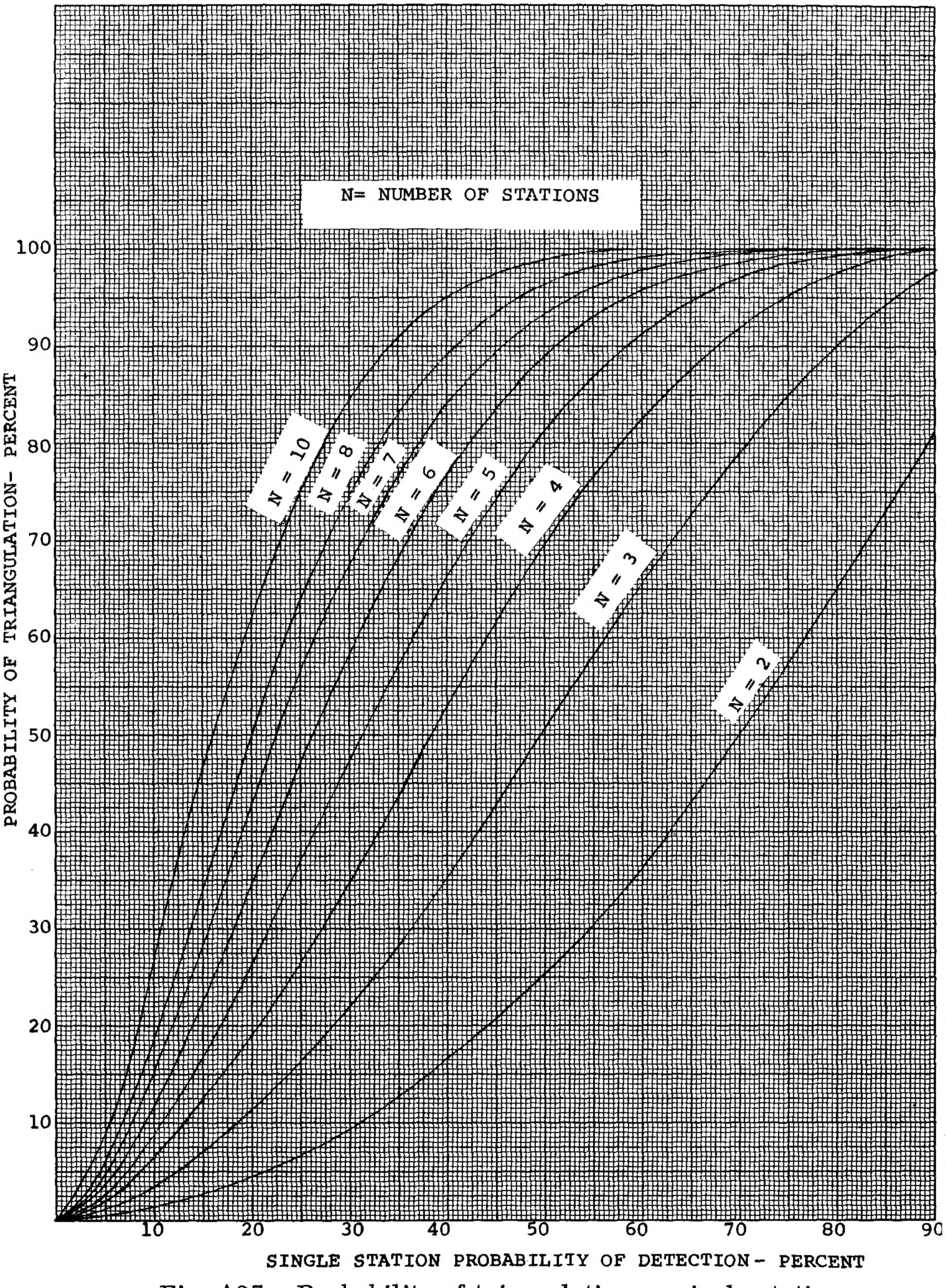


Fig. A37 - Probability of triangulation vs single station probability of detection

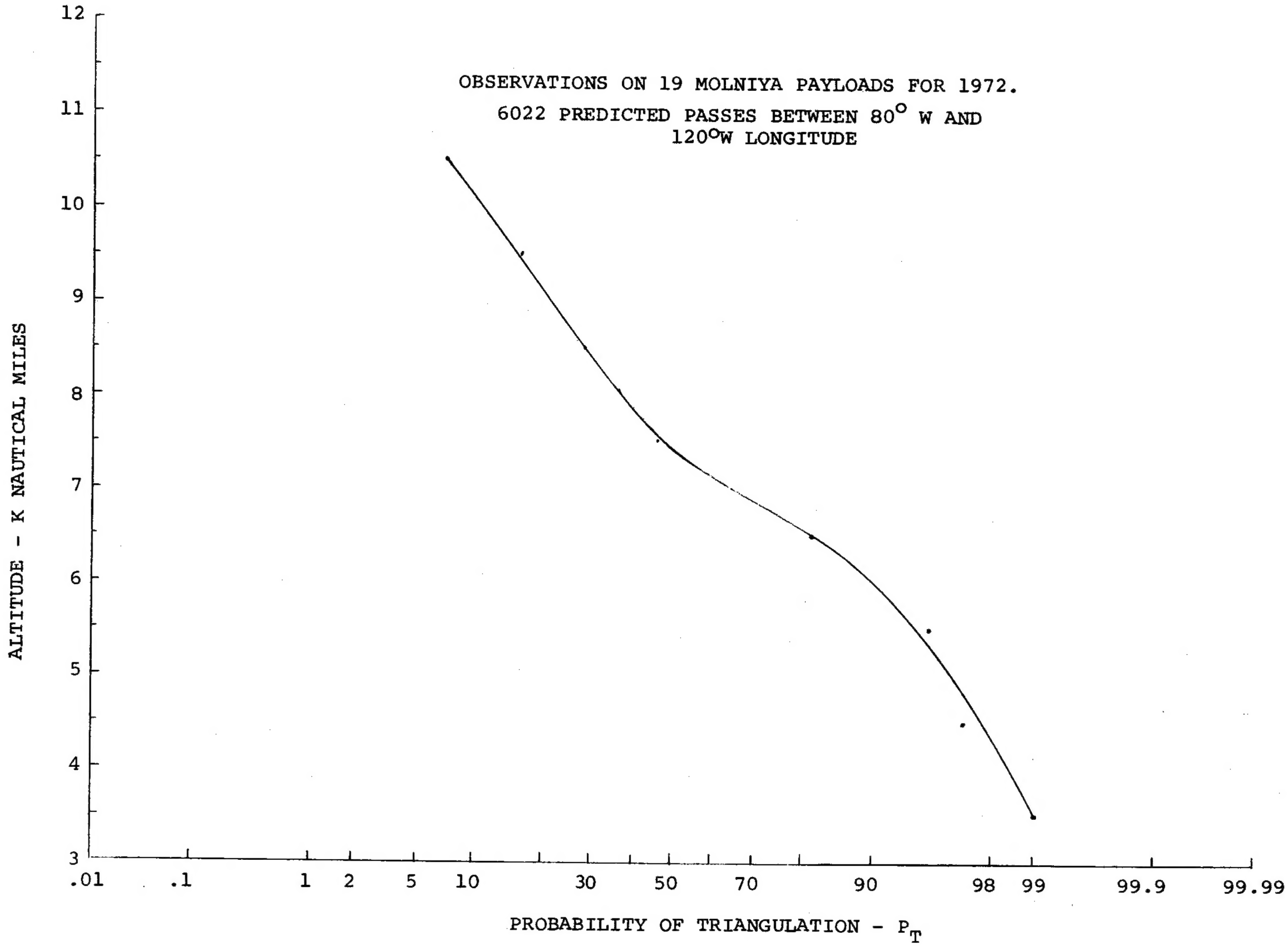


Fig. A38 - Probability of triangulation (P_T) vs altitude

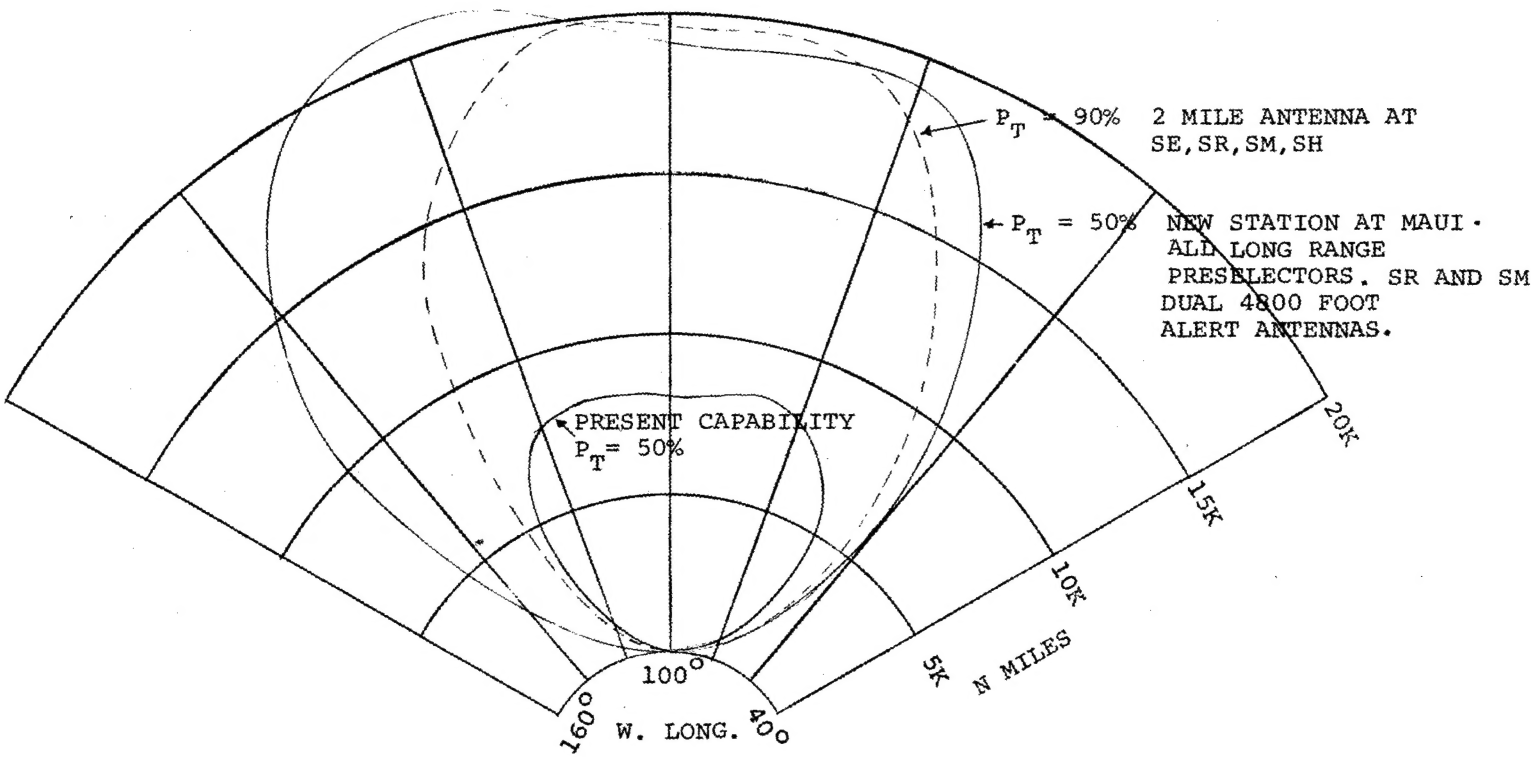


Fig. A39 - Coverage for Molniya-type payloads